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Tidal Salt Marsh Morphodynamics: A Synthesis

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ABSTRACT

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We now understand that, morphologically, natural tidal marshes are generally near or progressing rapidly toward dynamic equilibrium with sediment supply, vegetative growth and relative sea level, rather than far out of equilibrium on a slow evolution toward geologic maturity. The last fifteen years have been marked by major advances in the observation of sedimentation and accretion patterns in tidal salt marshes which reinforce this interpretation. This paper reviews and synthesizes advances since the late 1980s in our understanding of tidal salt marsh morphodynamics. Recent work has shown that allochthonous deposition patterns on the marsh are controlled primarily by source concentration, distance from that source, and duration of inundation (in turn determined by marsh elevation). Because deposition is proportional to inundation period, inorganic accretion tends to increase or decrease with accelerated or decelerated sea level rise, allowing the accretion rate to similarly fluctuate. Feedback between proximity to sediment source and duration of inundation causes relatively uniform accretion to be characterized by highest marsh elevations adjacent to tidal creeks. Since physical stress on vegetation increases with inundation, plant density and accretion of organic matter is reduced as inundation period increases, a pattern opposite to allochthonous deposition. Among systems dominated by allochthonous sediment, microtidal marshes are more reliant on storm and flood sedimentation and horizontally expand and retreat more quickly than macrotidal marshes, while the latter are more likely to persist during periods of accelerated sea level rise. The density, width and depth of salt marsh creeks all increase with increased tidal prism. Along barrier coastlines, greater tidal range is associated with more frequent inlet spacing, shallower channels, flood-dominance, and higher marsh elevation at equilibrium. Smaller tidal range results in greater inlet spacing, deeper channels, ebb-dominance and lower marsh elevation.

ADDITIONAL INDEX WORDS: *Coastal evolution, sediment transport, tidal wetlands.*

INTRODUCTION

Morphodynamics

Morphodynamics is the process by which morphology affects hydrodynamics in such a way as to influence the further evolution of the morphology itself (WRIGHT, 1995). Morphologic variability at small scales within tidal marshes, the relationship of the marsh to adjacent tidal channels and intertidal flats, and the overall morphology of tidal inlet/marsh systems are all highly impacted by feedback between marsh morphology and hydrodynamics. Morphodynamics thus provides a process oriented framework from which to better understand the stability of both natural and engineered tidal marshes in terms of what sustainable configuration may accommodate changes that occur in a state of dynamic equilibrium. Tidal salt marshes represent a relatively unusual case within the field of coastal morphodynamics because of the degree to which the characteristic morphology consists of both vegetative growth and sedimentary features.

Tidal salt marshes occur in temperate and high latitudes along coastal areas where physical energy is sufficiently low to allow establishment of salt tolerant grasses in the intertidal zone (PETHICK, 1984; REED, 1990; ALLEN and PYE, 1992; MITSCH and GOSSELINK, 1993); in tropical environments salt marshes are generally supplanted by mangroves. Fringing salt marshes develop in environments where waves are highly subdued, such as the shores of estuaries and lagoons. The gentle nearshore slopes common to macrotidal coasts and coasts adjacent to major river deltas also damp waves sufficiently to allow for fringing marshes. Otherwise the development of marshes requires a barrier to open water such as a spit or island. Extensive salt marshes tend to develop where the coastal plain is gently sloping and wide. Thus salt marshes are a more prominent component of passive rather than active continental margins. These externally imposed hydrodynamic and morphologic properties of the coast can predict the general potential for the development of salt marshes. Nonetheless, a physical understanding of the morphology of salt marshes at smaller scales benefits greatly from an appreciation of salt marsh morphodynamics.

The last decade has been marked by major advances in the observation of sedimentation and accretion patterns in tidal salt marshes. This review paper benefits particularly from the work of FRENCH and colleagues (STODDART *et al.*, 1989; FRENCH and STODDART, 1992; FRENCH and SPENCER, 1993; FRENCH *et al.*, 1995) and of LEONARD and colleagues (LEONARD and LUTHER, 1995; LEONARD *et al.*, 1995a,b; LEONARD, 1997) who have greatly extended our understanding of marsh hydrodynamics and firmly established the competing roles of sediment source proximity and local elevation in controlling spatial patterns of vertical accretion in tidal marshes dominated by allochthonous sediment. In addition, the recent literature has provided significant advances in our understanding of the generally negative response of vegetative growth and organic accretion to inundation (BRICKER-URSO *et al.*, 1989; DELAUNE *et al.*, 1990; NYMAN *et al.*, 1993, 1995b; CAHOON and REED, 1995; CALLAWAY *et al.*, 1997). In this paper we will also further develop morphodynamic models concerning interaction of tidal range, flood- versus ebb-dominance and equilibrium marsh height (FRIEDRICHS and AUBREY, 1988, 1994; FRIEDRICHS *et al.*, 1992; FRIEDRICHS, 1995).

These recent developments in the study of salt marsh morphodynamics highlight the rapid response of tidal marsh morphology to changes in physical forcing. Several articles particularly emphasize how marsh morphology is often indicative of a near equilibrium over time scales of decades to a few centuries, albeit constrained somewhat by its history (REED, 1990; FRENCH, 1991, 1994; OERTEL *et al.*, 1992; PETHICK, 1992; FRENCH and SPENCER, 1993; NYMAN *et al.*, 1993; ALLEN, 1997; DAY *et al.*, 1999). The fact that a marsh is relatively low or high or whether it partially or completely fills a lagoon does not mean that it is "young" or "old" in a geologic sense nor that it is necessarily in a certain stage of its evolution towards some extreme asymptote of "maturity". Tidal salt marshes have the potential of responding very rapidly to changes in forcing, and their local natural condition often represents a relatively short-term dynamic balance between relative sea level rise, sediment supply, and frequency/duration of inundation. In this regard, classical terms such as a "youthful" or "mature" marsh can be misleading.

The corollary of the above conclusions regarding tidal marsh morphodynamics is that engineered marshes which are not initially in dynamic equilibrium with physical forcing may very rapidly evolve away from their initial designs. The highly dynamic response of marshes to external forcing is now being recognized in recent investigations of tidal salt marsh engineering and restoration. In the context of marsh restoration, scientists, engineers and managers are now applying physical principles of marsh morphodynamics regarding duration of inundation (BRYANT and CHABRECK, 1998; ESSELINK *et al.*, 1998; ANISFELD *et al.*, 1999), sediment supply (REED and DE LUCA, 1997; FORD *et al.*, 1999; KUHN *et al.*, 1999), distance from sediment source (BOYER *et al.*, 1997; TURNER and BOYER, 1997; REED *et al.*, 1999) and general morphodynamic feedback (HALTINER *et al.*, 1997; TURNER and LEWIS, 1997; DAY *et al.*, 2000).

Organization

In this review paper, emphasis is placed on physical rather than biological processes. Of course, in discussing the morphology of marshes, plant-sediment interactions cannot be entirely ignored. Mechanisms by which marsh grass works to trap sediment and promote the accretion of both inorganic and organic matter are therefore discussed in some detail. This review is also biased toward more recent papers on the general subject of marsh morphodynamics, with most of the works referred to dating from the last fifteen years or so. Previous efforts which summarize earlier work include CHAPMAN (1974), PETHICK (1984), FREY and BASAN (1985), DIJKEMA (1987), STEVENSON *et al.* (1988), and ADAM (1990).

The paper is organized more or less in order of the increasing spatial scales characterizing various morphodynamic processes impacting the marsh. At a local scale, the next section describes how damping of velocity and turbulence by marsh grass is essential to the trapping of allochthonous sediment. The paper then discusses additional controls on the local accretion of allochthonous sediment, including the concentration and proximity of the sediment source and the inundation period. Next, spatial patterns of accretion within individual marshes are described in relation to the distribution of creeks, the frequency of storms, and the abundance of organic matter. Then feedback mechanisms are discussed between the frequency and duration of inundation (i.e., the "hydroperiod") and the rate of vertical accretion. For inorganic sediment, this feedback has a stabilizing effect, such that increases in the hydroperiod increase the accretion rate, and the increased accretion rate eventually decreases the hydroperiod once more. For organic accretion, however, the feedback is destabilizing. Increased hydroperiod increases stress on vegetation which then reduces the production of organic matter. This can decrease organic accretion which, in turn, further increases the hydroperiod. Resulting patterns of marsh waterlogging are discussed next, along with the effects of physical erosion and dredging.

The remaining five sections address larger scale interactions between marshes, tidal channels, and the effects of regional variations in tidal range. The fifth-to-last section describes the changing role of tides versus storms as tidal range decreases and why microtidal marshes are generally more sensitive to changes in relative sea level. Next, the influence of the marsh tidal prism on creek formation, creek evolution and equilibrium creek cross-section is discussed. The following section investigates imposed hydrodynamic and morphologic properties of the coast can predict the general potential for the development of salt marshes. Nonetheless, a physical understanding of the morphology of salt marshes at smaller scales benefits greatly from an appreciation of salt marsh morphodynamics.

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INTERACTION OF FLOW WITH MARSH GRASS

Colonization and Expansion

The settling of pioneer salt marsh vegetation requires a flat shoreline that is sheltered against waves such that the water is sufficiently quiet for the seeds to germinate (MITSCH and GOSSELINK, 1993; EISMA and DIJKEMA, 1997). Inundation must not be too frequent or prolonged; otherwise chemical stresses associated with waterlogging will prevent grass survival (DELAUNE *et al.,* 1983; REED, 1990). Generally marsh grasses cannot survive below mean tide level (FREY and BASAN, 1985; MCKEE and MENDELSSOHN, 1989) and are out competed by terrestrial plants above spring high tide (PETHICK, 1984). As soon as plants are established in an area conducive to salt marsh growth, the conditions for net deposition increase dramatically, with experience from man-made marshes suggesting deposition rates on the order of five times that of adjacent unvegetated flats (EISMA and DIJKEMA, 1997). Vertical accretion rates over decadal time frames are often as high as 1-2 cm/year, particularly on tidal marshes associated with river deltas (DELAUNE *et al.,* 1987; OENEMA and DELAUNE, 1988; LUTERNAUER *et al.,* 1995; WILLIAMS and HAMILTON, 1995; HENSEL *et al.,* 1999). Accretion rates of decimeters per year have recently been documented in tidal wetlands in the Yangtze delta (YANG, 1999b). Large, infrequent coastal storms can deposit several centimeters of sediment over a marsh surface during a single event (GOODBRED and HINE, 1995). Horizontal expansion of salt marshes by lateral spreading of rhizomes can also be remarkably rapid, with progradation rates of 10's to 100's of meters per year documented over time scales of a decade or more (WELLS and COLEMAN, 1987, Figure 1; REED, 1990; LUTERNAUER *et al.,* 1995; BOYER *et al.,* 1997). Equally rapid degradation can occur with loss of sediment supply or an accelerated rise in relative sea level (WELLS and COLEMAN, 1987, see Figure 1; DAY and TEMPLET, 1989; EVERS *et al.,* 1992; BOESCH *et al.,* 1994). Large-spread marsh plant death due to waterlogging or salt intrusion can lead to rapid loss of elevation on the order of 10-15 cm (DAY *et al.,* 2000).

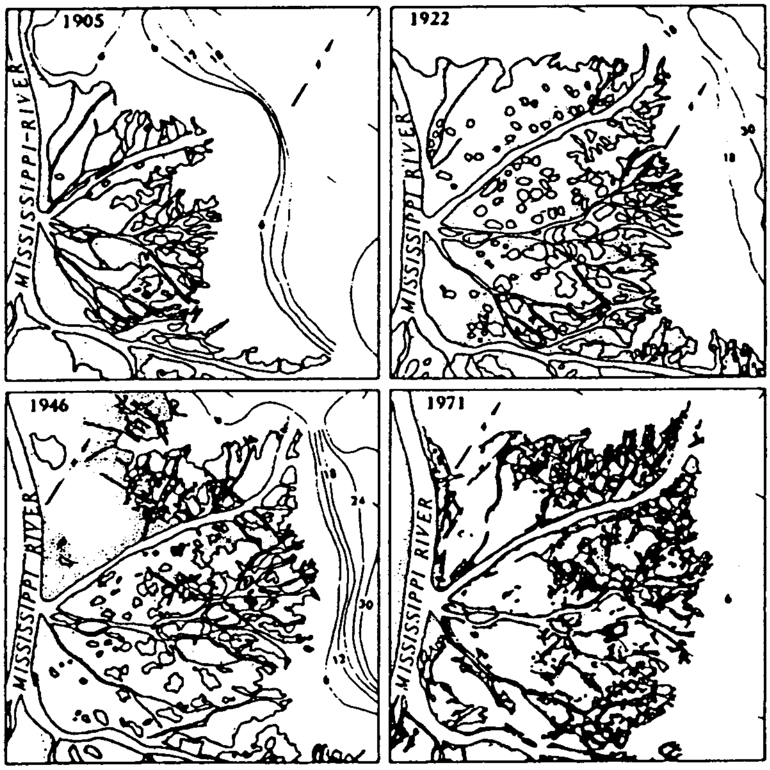

Figure 1. Horizontal expansion and degradation of the Cubit's Gap marsh, Louisiana, constructed from Coast and Geodetic Survey and U.S. Geological Survey charts. From Wells and Coleman (1987), published with permission of *Estuarine Coastal and Shelf Science.*

The ability of salt marsh to rapidly accrete vertically and horizontally under favorable conditions reinforces the notion that natural marshes can quickly respond to external forcing. Generally, natural tidal salt marshes are more properly characterized as being near or progressing rapidly toward a dynamic equilibrium with respect to local sediment supply and sea level, rather than being far out of equilibrium on a slow evolution toward geologic "maturity". The classical model of a salt marsh very slowly accreting upward and outward and as it fills a lagoon (LUCKE, 1934) is applicable only to restricted circumstances where the lagoon boundaries and sea level remain fixed, and where sediment input gradually and continually fills the lagoon (OERTEL *et al.*, 1992). Even under these circumstances, the vertical and horizontal extent of the marsh grass is continually near dynamic equilibrium with the slowly changing boundary condition imposed by the adjacent depth of the lagoon.

Hydrodynamics

Profiles of velocity measured within marsh grass in the field (LEONARD and LUTHER, 1995, Figure 2; LEONARD *et al.*, 1995a; CHRISTIANSEN *et al.*, 2000) and through real and artificial marsh grass in the laboratory (BURKE, 1982; PETHICK *et al.*, 1990; SHI *et al.*, 1996) clearly demonstrate the marked reduction of flow velocity within marsh grass relative to unimpeded flow above its top. Flow within marsh grass tends to display very little vertical shear along with a corresponding reduction in turbulence, properties which favor rapid sediment settling and which prevent sediment resuspension (LEONARD and LUTHER, 1995; CHRISTIANSEN *et al.*, 2000). For a given pressure gradient, flow speed and turbulence within the marsh grass both decrease with increased stem density (LEONARD *et al.*, 1995a, Figure 3). If the marsh grass is entirely submerged, flow near the top and above the canopy is more highly sheared and turbulent, tending to form a logarithmic profile above the less sheared flow within the canopy itself (BURKE, 1982; LEONARD and LUTHER, 1995, see Figure 2). The settling rate of sediment is reduced within the portion of the flow entirely above the marsh grass, especially under conditions of extremely high tides or storm surges supplemented by wind waves (LEONARD *et al.*, 1995a).

The energy of tidal flow within marsh grass typically decreases by an order of magnitude or more (LEONARD and LUTHER, 1995; CHRISTIANSEN *et al.*, 2000) relative to unvegetated areas, and wind wave energy is similarly dissipated under most conditions (BRAMPTON, 1992; MOELLER *et al.*, 1996, 1999; YANG, 1998). Flow speed within the canopy is inversely related to distance from the creek edge (CHRISTIANSEN *et al.*, 2000), although vegetative cover is overall a more important control (LEONARD *et al.*, 1995a). Dye tracer experiments reported by LEONARD (1997) indicate distinct flow patterns on the marsh surface over the course of an inundation event. Initially flow is normal to the creek banks as water overtops the channel banks and flows down over the associated levees. The flow within the marsh grass then tends to follow topographic lows. Once the water level exceeds most of the topographic highs on the marsh, predominantly landward sheet flow is established. After slack water, the flow direction reverses and water moves seaward as sheet flow until the marsh highs re-emerge. For

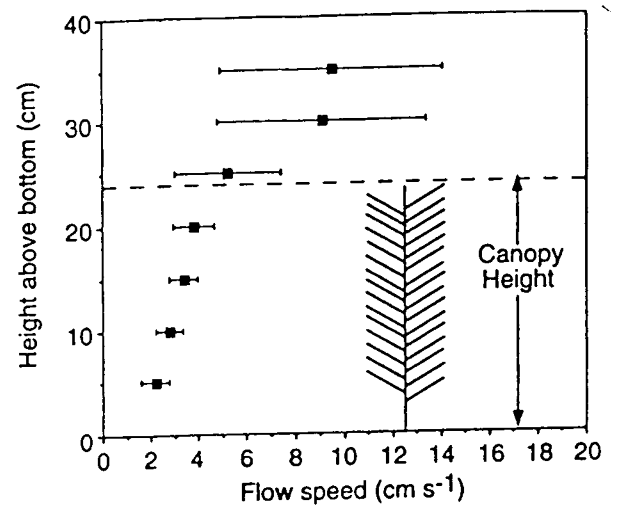

Figure 2. Speed data collected in tidal flows through and above a *Distichlis spicata* canopy (including schematic sketch of a plant) near Cedar Creek, Florida. From Leonard and Luther (1995), published with permission of *Limnology and Oceanography*.

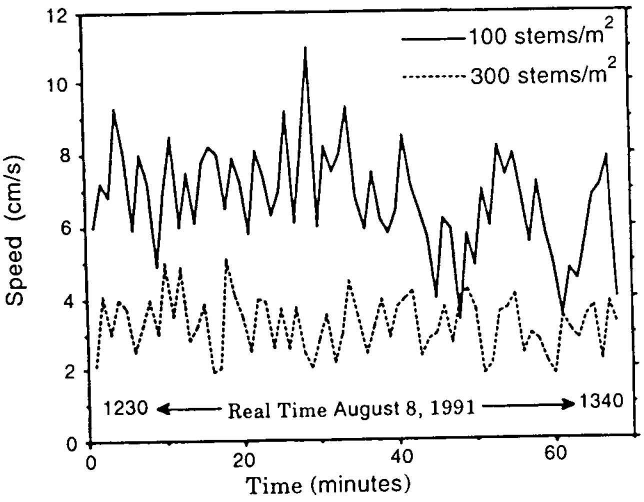

Figure 3. Example of flow speeds measured during mid to late flood in two areas in the interior of a *Juncus roemerianus* marsh near Cedar Creek, Florida. From Leonard *et al.* (1995a), published with permission of *Journal of Coastal Research*.

the remainder of the ebb, flows follows topographic lows once more. The maximum velocity observed during overmarsh flows by LEONARD (1997) was only 16 cm/s due to frictional effects and plant baffling.

Trapping of Allochthonous Sediment

The ability of marsh grass to drastically slow water velocity is fundamental to the very existence of marshes dominated by inorganic sediment (PETHICK, 1984; EISMA and DIJKEMA, 1997). Marsh grass reduces the velocity of flow through the grass so drastically that sedimentation usually occurs continually throughout the period of inundation (PETHICK, 1984; LEONARD *et al.*, 1995a; CHRISTIANSEN *et al.*, 2000). This is made clear by a general decrease in suspended sediment concentration with time at any one point during an inundation event (LEONARD, 1997, Figure 4). This helps explain why fundamental patterns of inorganic sediment deposition are often insensitive to the particular suite of species present (FRENCH and SPENCER, 1993; LEONARD, 1997). As long as the marsh vegetation acts to reduce velocity to a level at which continual deposition of sediment occurs, the local rate of allochthonous deposition may be more sensitive to the duration of inundation, the sediment load and the sediment fall velocity (see the following section).

Nonetheless, there are specific features of marsh grass morphology which can further affect inorganic sediment accretion. The accretion rate of inorganic sediment increases with grass stem density (OENEMA and DELAUNE, 1988; REJMANEK *et al.*, 1988; NYMAN *et al.*, 1995a) because greater stem density further reduces velocity (LEONARD and LUTHER, 1995; LEONARD *et al.*, 1995a, see Figure 3). *Juncas roemerianus* and *Spartina patens* tend to grow in denser stands than *Spartina alterniflora*, which may explain why higher rates of accretion in given storm events are associated with the former species (NYMAN *et al.*, 1995a). Greatest deposition rates in summer on some marshes is possibly due to enhanced baffling of overmarsh flows when the availability of live plant material on the marsh surface is at a maximum (LEONARD, 1997). Also, certain species are more tolerant of inundation; the presence of such species ultimately determines the lower limit of the marsh (PETHICK, 1984). Some species of marsh grass collect suspended sediment on the stems and leaves themselves, including *Spartina alterniflora* and *Phragmites australis*, enhancing mineralogical deposition on the order of 50% (STUMPF, 1983; LEONARD *et al.*, 1995a; EISMA and DIJKEMA, 1997), whereas other varieties do not, such as *Juncus*, *Aster tipolium*, *Salicornia* and *Puccinellia* (FRENCH and SPENCER, 1993; LENOARD *et al.*, 1995a; EISMA and DIJKEMA, 1997).

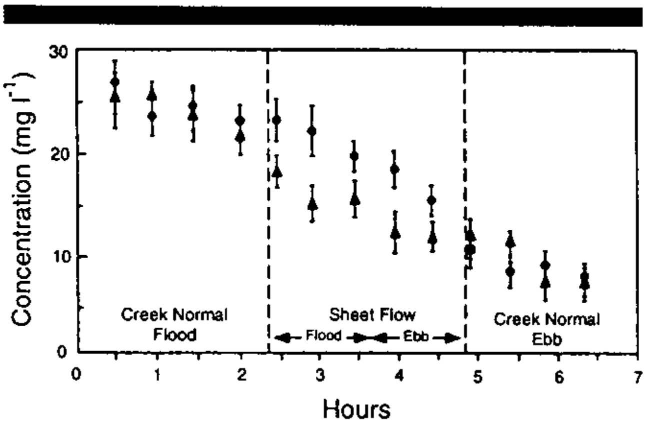

Figure 4. Typical overmarsh total suspended solids (TSS) concentrations measured at a seaward creek margin site (triangles) and a landward creek margin site (circles) over an inundation event in a marsh containing *Spartina alterniflora* and *Juncus roemerianus* along Bradley Creek, North Carolina. From Leonard (1997), published with permission of *Wetlands*.

ADDITIONAL CONTROLS ON ACCRETION RATE OF ALLOCHTONOUS SEDIMENT

Concentration of Source

The supply of sediment to the marsh surface is proportional to the concentration of suspended sediment adjacent to the marsh surface, whether the source be a marsh creek, lagoon, tidal flat or upland area (FRENCH, 1993, 1994; LEONARD, 1997; REED *et al.*, 1999). Any process which increases sediment concentration adjacent to the marsh surface will tend to increase the marsh accretion rate (LEONARD, 1997, Figure 5). Physical processes which tend to increase concentration adjacent to the marsh include local suspension by increased tidal velocity (LEONARD *et al.*, 1995b; LEONARD, 1997; REED *et al.*, 1999; CHRISTIANSEN *et al.*, 2000), wind waves (REED, 1988; LEONARD *et al.*, 1995b; DAY *et al.*, 1998), proximity to the

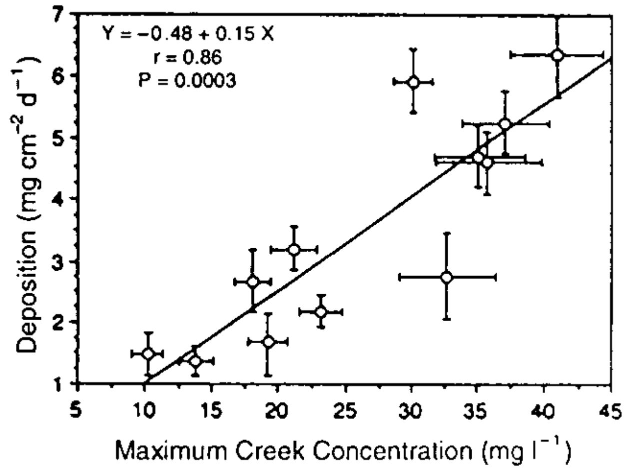

Figure 5. Relationship between rate of surficial deposition on a *Spartina alterniflora* marsh at Bradley Creek, North Carolina, and maximum TSS concentration in the adjacent creek. Deposition data consist of basinwide means for each sampling event. From Leonard (1997), published with permission of *Wetlands*.

estuarine turbidity maximum (WARD *et al.*, 1998), and an increase in the "background" concentration due to offshore erosion (PETHICK and REED, 1988; REED, 1989; FRENCH and SPENCER, 1993). Regional geology also affects the background concentration. For example, glacial processes have removed most of the fine sediment from the coastal region of New England. In contrast, rivers flowing across coastal plains in the southeastern U.S. are literally red with clay (FREY and BASAN, 1985). As will be discussed in a later section, flood-dominance of velocity within marsh creeks can also be expected to increase the source concentration, whereas ebb-dominance can be expected to decrease source concentration.

Enhanced biological activity in summer can increase or decrease the background concentration in adjacent tidal flats and channels. Substrate disturbance due to bioturbation in channels and on flats tends to increase suspended sediment concentration on the marsh (WOLAVER *et al.*, 1988a; GARDNER *et al.*, 1989; LEONARD *et al.*, 1995a), whereas substrate stabilization by bacteria and microalgae (FROSTICK and MCCAVE, 1979) and enhanced sediment aggregation due to biological processing of fine particles (FREY and BASAN, 1985; FRENCH and SPENCER, 1993) tends to reduce sediment concentration. The result can be a strong biologically induced seasonal signal in the accretion rate on the surface of the marsh (HUTCHINSON *et al.*, 1995; LEONARD *et al.*, 1995a; LEONARD, 1997, Figure 6).

Inundation and Marsh Elevation

Marsh sedimentation occurs continuously throughout individual flooding events, although the sedimentation rate tends to decrease through the duration of the event (LEONARD *et al.*, 1995a, Figure 7). Nonetheless, it follows that the total amount of sediment deposited during a single flooding event will increase with the duration of that event at any given location (WOLAVER *et al.*, 1988b; LEONARD, 1997, Figure 8a). Local tidal height, a surrogate for duration of inundation in tidally-dominated marshes, also shows a positive correlation with accretion (FRENCH and SPENCER 1993), as does the cumulative duration of flooding over several seasons (CAHOON and REED, 1995, Figure 8b).

Since there are multiple contributions to the local rate of accretion, it can be difficult to empirically isolate the role of the length of inundation using a limited number of data points (LEONARD, 1997). An alternative observational approach which incorporates the length and frequency of inundation is to examine the relationship between marsh elevation and accretion rate. Portions of the marsh which are higher with respect to the tide will be flooded for a shorter duration during each event, and therefore will receive relatively less sediment. An inverse relationship between marsh elevation and accretion rate has been confirmed observationally in several marshes (BRICKER-URSO *et al.*, 1989; FRENCH and SPENCER, 1993; STODDART *et al.*, 1989; FRENCH *et al.*, 1995, Figure 9; CAHOON *et al.*, 1996; LEONARD, 1997; ESSELINK *et al.*, 1998).

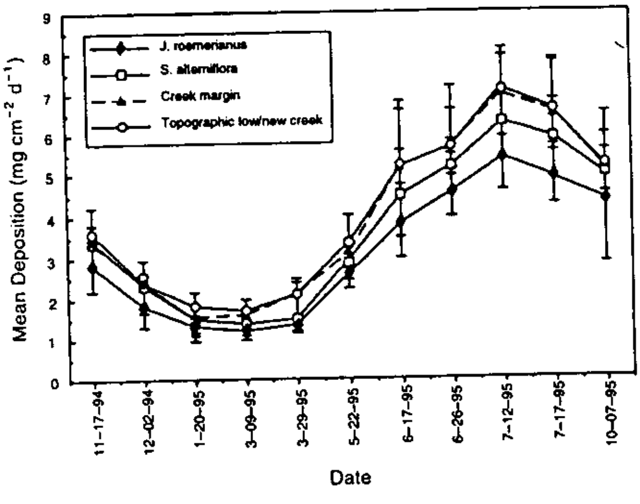

Figure 6. Seasonal surficial deposition rates measured by sediment traps deployed in different subenvironments of the Bradley Creek marsh, North Carolina. Each data point indicates the mean of all sediment traps retrieved within the designated environment. Both bioturbation and deposition rates are highest in the summer. From Leonard (1997), published with permission of *Wetlands*.

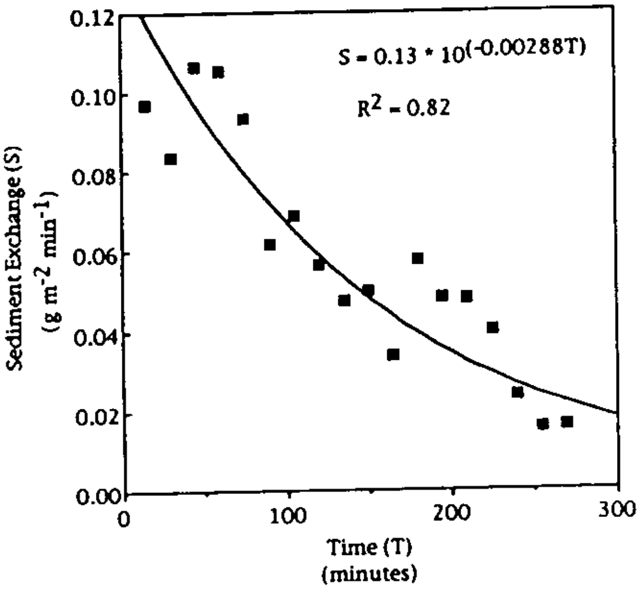

Figure 7. Sedimentation rate in the interior of a *Juncus roemerianus* marsh near Cedar Creek, Florida, inferred from the rate of change in suspended solid concentration in the overlying water column. From Leonard *et al.* (1995a), published with permission of *Journal of Coastal Research*.

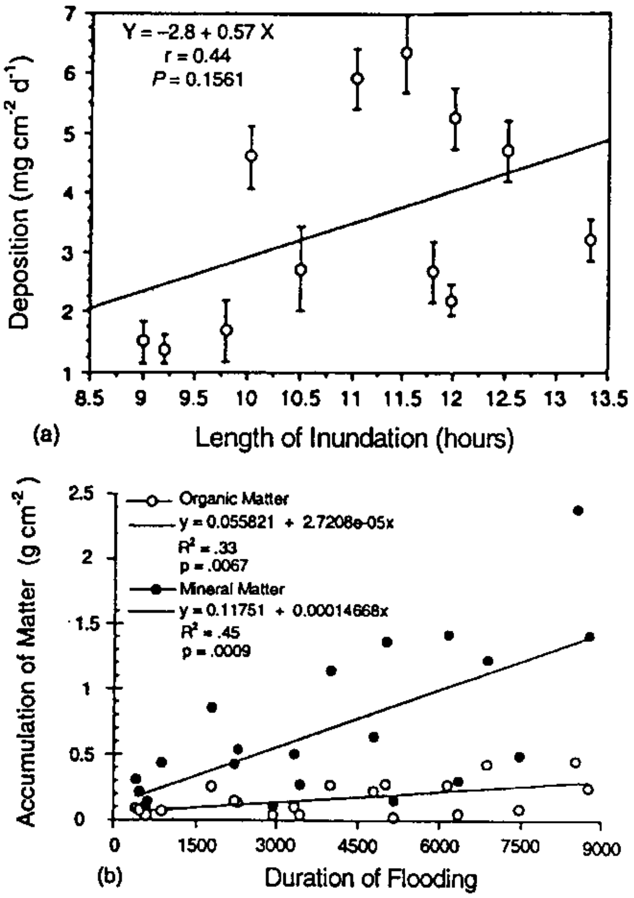

Figure 8. Relationship between sediment accumulation and duration of inundation in *Spartina alterniflora* marshes: (a) For individual events averaged over the marsh at Bradley Creek, North Carolina (from Leonard, 1997, published with permission of *Wetlands*); (b) for individual plots in a marsh near Cocodrie, Louisiana, with inundation integrated over an 18 month period (from Cahoon and Reed, 1995, published with permission of *Journal of Coastal Research*).

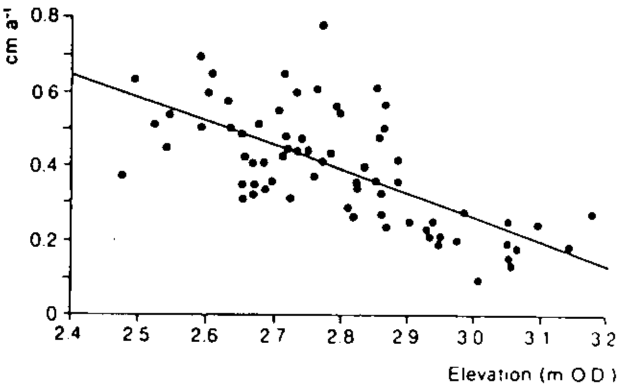

Figure 9. 1986 to 1991 mean annual accretion plotted against elevation for locations throughout the species rich Hut marsh, North Norfolk, U.K. From French *et al.* (1995), published with permission of *Journal of Coastal Research*.

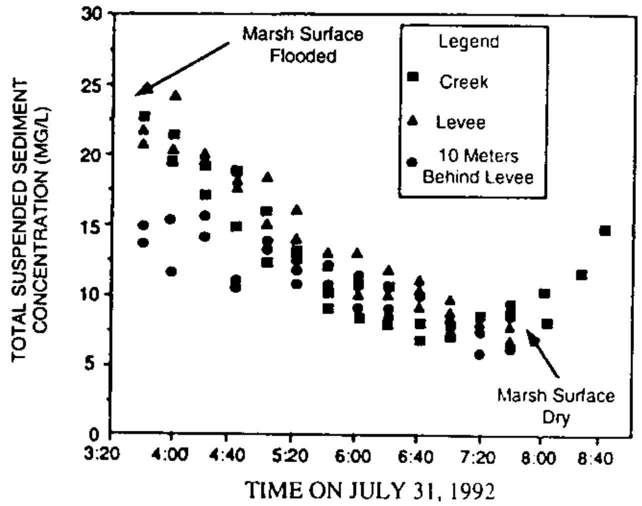

Figure 10. TSS concentration collected over a tidal cycle on the surface of a marsh and in the adjacent tidal creek near Cedar Creek, Florida. From Leonard *et al.* (1995a), published with permission of *Journal of Coastal Research*.

Proximity to Source

Because marsh grass almost always slows velocity sufficiently to allow continual sedimentation, sediment will immediately begin to settle as water enters the marsh. This will cause the concentration of suspended sediment in a given marsh water parcel to decrease with time, and it follows that concentration over the marsh surface will generally be observed to decrease with distance into the marsh (FRENCH and STODDART, 1992; FRENCH and SPENCER, 1993; WANG *et al.*, 1993; LEONARD *et al.*, 1995a, Figure 10; LEONARD, 1997; REED *et al.*, 1999; CHRISTIANSEN *et al.*, 2000). It also follows logically that the deposition rate for inorganic sediment will generally decrease with distance away from the source of sediment laden water, which is often an adjacent tidal creek or tidal flat — see the following section (OENEMA and DELAUNE, 1988; REED, 1988; STODDART *et al.*, 1989; ALLEN, 1992; REED, 1992; FRENCH and SPENCER, 1993, Figure 11, 6; KASTLER and WIBERG, 1996; LEONARD, 1997; WARD *et al.*, 1998).

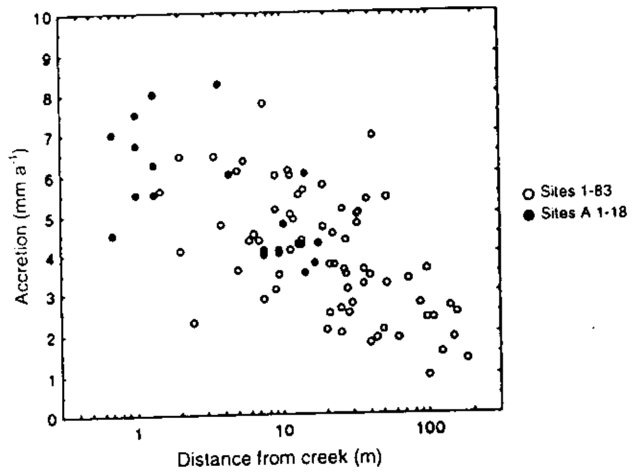

Figure 11. 1986 to 1991 mean annual accretion plotted against distance from the nearest creek for locations throughout the species rich Hut marsh, north Norfolk, U.K. From French and Spencer (1993) published with permission of *Marine Geology*.

SPATIAL PATTERNS OF MARSH SEDIMENTATION

Control by Tidal Channels

Because of the rapid decrease in suspended sediment concentration and deposition rate with distance from the sediment source, tidally dominated marshes exhibit patterns of inorganic accretion largely controlled by the distribution of salt marsh creeks (FRENCH and SPENCER, 1993; LEONARD, 1997; ESSELINK *et al.*, 1998; REED *et al.*, 1999). Very strong gradients in the marsh deposition rate are seen adjacent to creeks over distances of only a few 10's of meters (FRENCH and SPENCER, 1993; LEONARD, 1997, Figure 12; REED *et al.*, 1999). Rapid deposition immediately adjacent to tidal channels causes topographically higher marsh levees to form, paralleling the sides of the marsh creeks (LEONARD, 1997, see Figure 12; ESSELINK *et al.*, 1998, Figure 13). Thus at smaller scales immediately adjacent to the marsh creeks, the larger scale relationship between marsh elevation and accretion rate may be reversed (FRENCH and SPENCER, 1993; ESSELINK *et al.*, 1998, see Figure 13), with locally higher elevations directly correlated with higher rates of deposition. At larger scales, the relationship between elevation and accretion still remains, with lower lying portions of the marsh still receiving additional sedimentation.

Because of the dependence of the sedimentation rate on fall velocity, the grain size of inorganic marsh sediment is also observed to generally decrease with distance away from its source in tidal creeks (ALLEN, 1992, Figure 14; FRENCH and SPENCER, 1993; LUTERNAUER *et al.*, 1995; WOOLNOUGH *et al.*, 1995; KASTLER and WIBERG, 1996). On the marsh levees, the deposition of fine sand and coarse silt is possible, while fine silt and clay are more typical of the inner marsh. The dependence of fall velocity on grain size also means that the distance to which sediment is transported across the marsh will depend on the degree of flocculation (CHRISTIANSEN *et al.*, 2000), which, in turn, varies seasonally according to biological activity. In summer, aggregation may increase fall velocities, favoring deposition closer to inflow areas. In winter, biological aggregation is decreased, and sediment may be more widely dispersed throughout the marsh (FREY and BASAN, 1985; FRENCH and SPENCER, 1993).

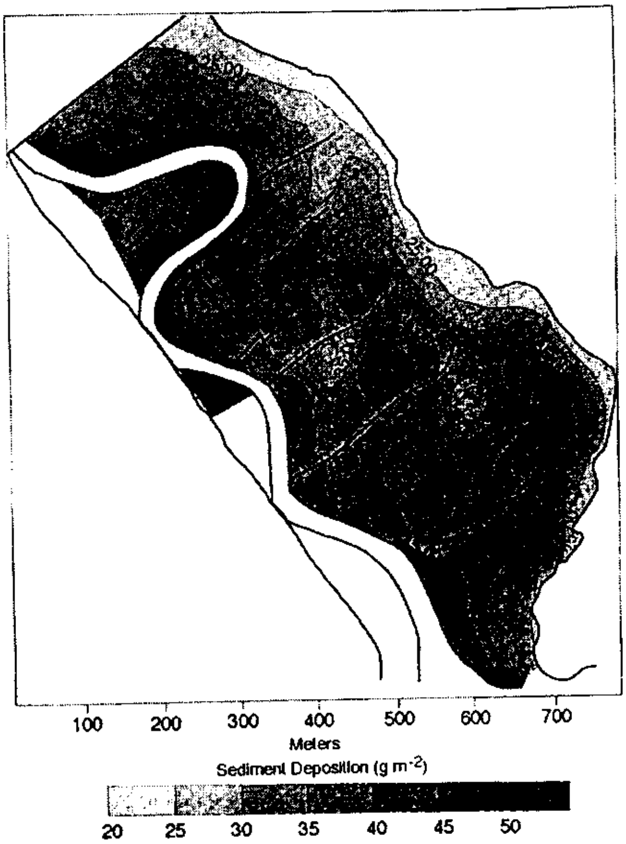

Figure 12. Map showing sediment deposition patterns at Bradley Creek marsh, North Carolina. Deposition rates were determined by calculating the mean for each of the 101 sampling sites monitored between October 1994 and October 1995. From Leonard (1997), published with permission of *Wetlands*.

Physical Processes Independent of Tidal Channels

On very high tides and storms, the tide overtops the entire marsh, and the creeks no longer provide a first order control on hydrodynamics or sedimentation patterns within the marsh (FRENCH and STODDART, 1992). In this case, sedimentation patterns are likely to occur in

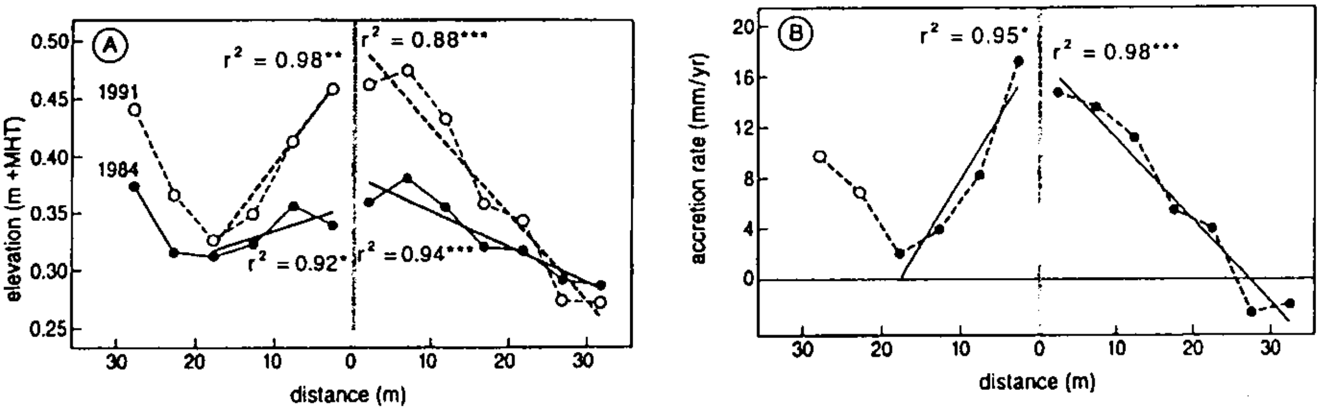

Figure 13. Example of levee development on either side of a minor creek in a marsh along the species rich Dollard Estuary, the Netherlands: (a) elevations in 1984 and 1991 and (b) vertical accretion rate as a function of distance away from each side of the creek. Points further than 20 meters to the "left" of the this creek were located on the levee of the next neighboring minor creek. From Esselink *et al.* (1998), published with permission of *Journal of Coastal Research*.

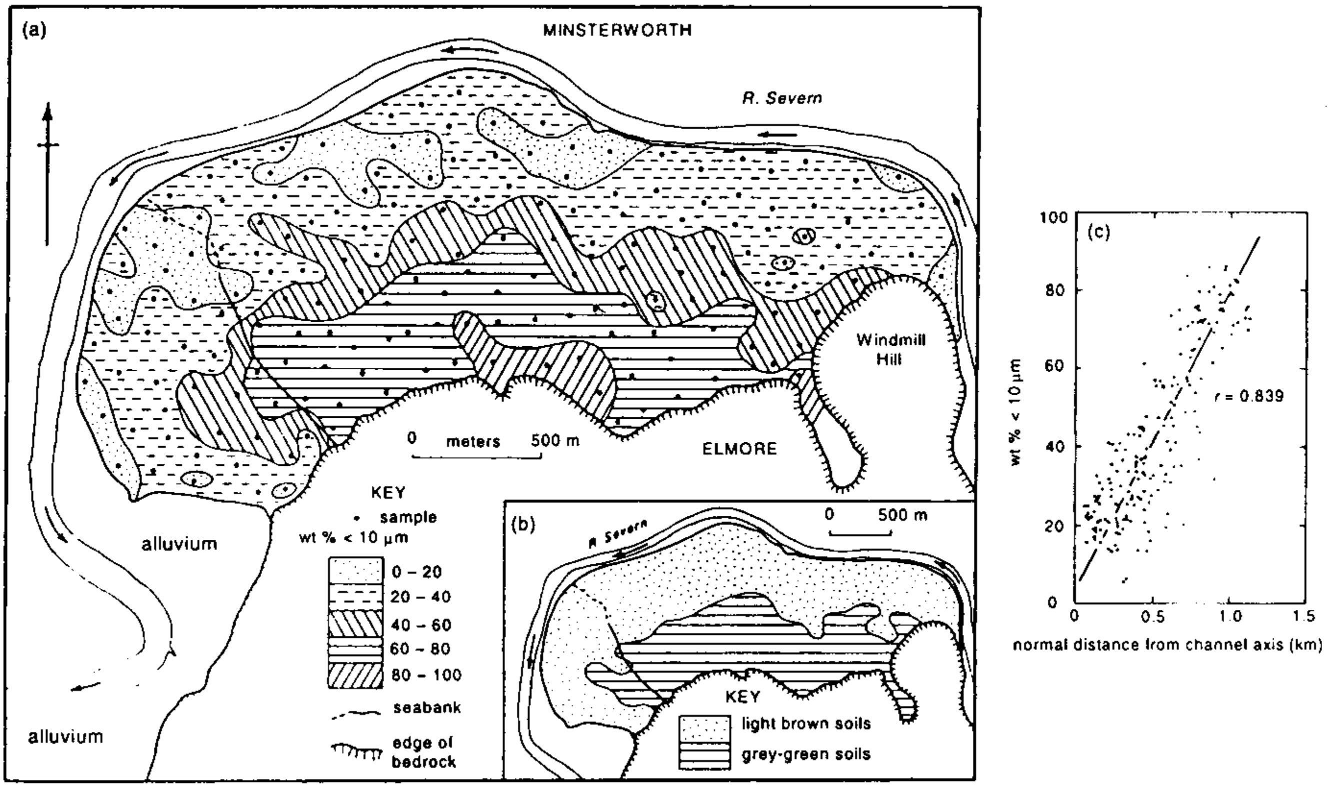

Figure 14. Soil properties in a reclaimed tidal salt marsh along the Severn estuary: (a) textural pattern of soil-subsoil materials; (b) color pattern of soil-subsoil materials; (c) dry weight percent less than 10 microns as a function of distance from the axis of the Severn Estuary, U.K. From Allen (1992), published with permission of *Sedimentary Geology*.

bands more or less parallel to the seaward edge of the marsh where the surge originated (FREY and BASAN, 1985). If the water is sufficiently deep or waves are superimposed upon the surge, the marsh grass may no longer be capable of keeping velocity low enough to insure continual deposition of mud over the lower marsh (PETHICK, 1992; LEONARD *et al.*, 1995a). The line of maximum deposition may then occur some distance in from the edge of the marsh, where the marsh is still high enough to dampen velocity throughout the water column (STEVENSON *et al.*, 1988; DAY *et al.*, 1998). Since the high marsh is flooded mainly by extreme tides and surges, and tidal creeks there are generally less well developed, accretion of inorganic sediment on the high marsh is more dependent on extreme events (FRENCH and SPENCER, 1993) and is more likely to be characterized by zonation paralleling the general outline of the entire marsh (FREY and BASAN, 1985). The locus of maximum deposition shifts seaward again if flooding is so extreme that not even the high marsh can effectively damp wind waves. Under these conditions, the marsh begins to act morphodynamically like a beach (PETHICK, 1992). More erosion (or less deposition) will occur high on the marsh relative the lower marsh or adjacent tidal flats and the typical reduction in grain size between tidal flat and marsh will be reversed.

A reversal in the normal trend toward finer grain size away from tidal channels may also occur due to terrestrial runoff entering the upper marsh (FREY and BASAN, 1985), due to overwash of barriers beaches during storms (KASTLER and WIBERG, 1996; COURTEMANCHE *et al.*, 1999), or due to aeolian transport from dunes (REDFIELD, 1972; FRENCH and SPENCER, 1993). Since runoff, overwash and aeolian transport are not dependent on the tidal creek system, the distribution of sandier sediments from these sources also tends to parallel the outline of the marsh.

Organic Material

The organic portion of accreted material in tidal marshes is a combination of plant detritus, the remains of microbes, phytoplankton and animals, fecal pellets and partially preserved *in* situ roots and rhisomes (FREY and BASAN, 1985). Where marsh accretion is dominated by organic matter, such as in many Louisiana and New England marshes, the accreted material is typically dominated by tightly interlocking root and rhisome networks (STEVENSON *et al.*, 1988; NYMAN *et al.*, 1993). In meso- and macrotidal marshes, the organic percentage of accreted material often increases with marsh elevation and/or distance into the interior of the marsh (PESTRONG, 1972; FRENCH and SPENCER, 1993; LEONARD *et al.*, 1995a; KASTLER and WIBERG, 1996, Figure 15; WARD *et al.*, 1998). These patterns can be explained in part by decreased delivery of mineral matter to these areas by tidal channels relative to the preservation of *in situ* organic material (CRAFT *et al.*, 1993; LUTERNAUER *et al.*, 1995; KASTLER and WIBERG, 1996). Likewise, very low organic content of marsh sediment may be related simply to very high rates of inorganic mineral sedimentation (YANG, 1999a). In some cases, however, total organic deposition may be higher on the lower and/or seaward marsh due to tidal deposition of allochthonous organic matter (CAHOON and REED, 1995, see Figure 8b; FRENCH *et al.*, 1995). Greater accretion of *in situ* organic matter is favored on the high marsh due to the decrease in flooding stress experienced by marsh grass at higher elevations and the associated tendency for increased grass and root density (PETHICK, 1984; DELAUNE *et al.*, 1990; DE LEEUW and BUTH, 1991; NYMAN *et al.*, 1993, 1995b; DAY *et al.*, 1999). On the microtidal coast of Louisiana, increased organic content of marsh sediment is also correlated with reduced salinity because *Spartina patens*, the dominant species in less saline areas, is associated with higher rates of production and slower rates of decomposition than *Spartina alterniflora*, the dominant species at more saline sites (NYMAN *et al.*, 1990, 1995b).

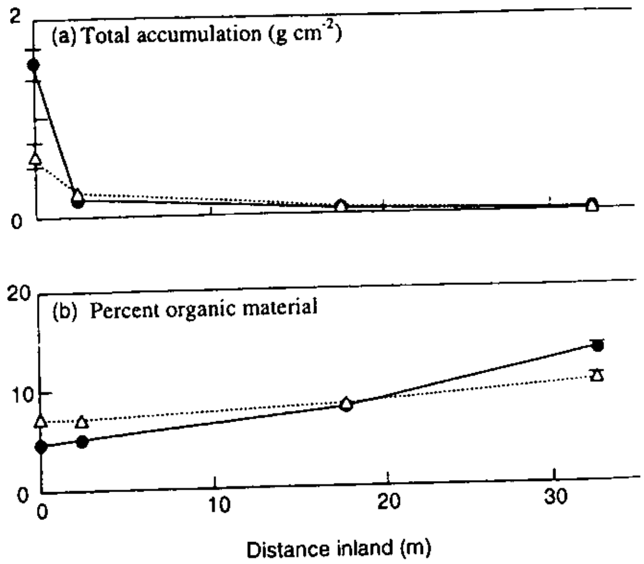

Figure 15. Variation of sediment characteristics from marsh edge to interior of two *Spartina alterniflora* marshes near Hog Island Bay, Virginia, averaged between November 1991 and October 1992: (a) total accumulation; (b) percent organic material. Circles = Chimney Pole Marsh, triangles = Phillips Creek Marsh. From Kastler and Wiberg (1996), published with permission of *Estuarine Coastal and Shelf Science*.

FEEDBACK ASSOCIATED WITH MARSH HYDROPERIOD

Hydroperiod, Sea Level, and Inorganic Sedimentation

"Hydroperiod" (REED, 1990) is a term which incorporates the frequency and duration of both tides and surges which inundate a given location within a marsh. The greater a site's hydroperiod, the greater the percentage of time that site spends submerged. An increase in hydroperiod favors enhanced deposition of allochthonous sediment but increases the stress on marsh vegetation (see previous sections). Reed (1990, Figure 16) summarizes interactions between tides, storms, hydroperiod, deposition, vegetative growth, sea level, marsh elevation and net vertical accretion.

The influence of hydroperiod on inorganic deposition leads to a profound mechanism for morphodynamic feedback in response to sea level rise (Krone, 1988; Allen, 1990, 1997; Reed, 1990; French, 1991, 1993; Callaway *et al.*, 1996; Day et al, 1999). If future sea level rises faster than the present rate of vertical marsh accretion, the elevation of the marsh will fall, increasing the hydroperiod. As we saw in the third section of the paper, lower elevation and increased hydroperiod favor an increase in the rate of inorganic sedimentation. This, in turn, has the potential of increasing the rate of accretion sufficiently to match the enhanced rate of sea level rise (assuming the additional sediment is available). Conversely, if future sea level rise is less than the present rate of vertical accretion, the marsh will rise, decreasing the hydroperiod, decreasing inorganic sedimentation, and reducing the rate of accretion. Thus changes in hydroperiod allow marshes dominated by allochthonous sediment to continually adjust their rate of accretion to remain near equilibrium with fluctuating rates of rise in sea level. In general, a marsh in dynamic equilibrium with quickly rising sea level will be lower in elevation than a similar marsh responding to a slower rate of sea level rise. Another consequence of hydroperiod's control on sedimentation is that a marsh dominated by allochthonous sediment accreting under a stable sea level can theoretically never make the evolutionary transition to upland. Since the high marsh will receive less and less sediment as it accretes, it can only approach, at an exponentially decreasing rate, a maximum level somewhat below the level of the highest spring tides (Pethick, 1981, 1984; Allen, 1990; French, 1994). However, additional accretionary forces act on many marshes, including land runoff, barrier overwash, storm surges, and *in situ* accretion of organic matter. The upper boundary of the marsh will then be blurred with respect to tidal elevation, marked instead by gradual out-competition by terrestrial plants (Pethick, 1984). In tectonically active coastlines subjected to uplift or in areas of isostatic rebound, the associated reduction in hydroperiod will eventually cause inorganic sedimentation on the marsh surface to be minimal (Reed, 1990). *In situ* accretion of organic matter may continue until the marsh is elevated above the range of tidal and storm surge inundation and a transition to an upland environment occurs.

Interactions of Hydroperiod, Subsidence and Sediment Supply

Marsh subsidence due to sediment compaction (Allen, 1990; Nyman *et al.*, 1993; Boesch *et al.*, 1994; Cahoon *et*

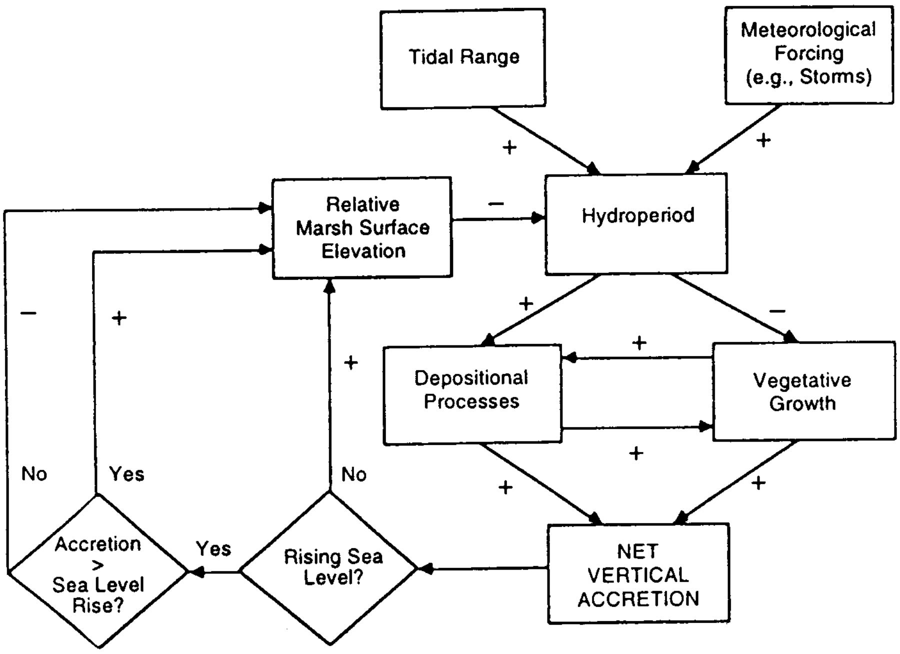

Figure 16. The interaction of tides, storms, hydroperiod, deposition, vegetative growth, sea level, marsh elevation and net vertical accretion. If the correlation between two components is positive, the arrow connecting the two boxes displays a "+", if the correlation is negative, the arrow displays a "-". From Reed (1990), published with permission of *Progress in Physical Geography*.

al., 1995; DAY *et al.*, 1999) or extraction of fluids (KEARNEY and STEVENSON, 1991; WHITE and TREMBLAY, 1995; DIJKEMA, 1997) will lower marsh level with respect to the tide in a manner analogous to sea level rise. Since hydroperiod increases with marsh subsidence, limited subsidence should also enhance the deposition of allochthonous sediment. Assuming enhanced deposition of allochthonous sediment is sufficient to maintain a dynamic equilibrium, the equilibrium surface of the marsh will become progressively lower as the rate of subsidence increases.

Duration of inundation also provides a feedback mechanism for maintaining a dynamic equilibrium in response to variations in the suspended sediment supply introduced to the marsh (FRENCH, 1991, 1994). If sediment supply decreases under a constant rate of relative sea level rise, the elevation of the marsh will drop with respect to the tide, and the hydroperiod will increase. A greater portion of the (albeit reduced) suspended sediment load will now be deposited on the marsh with each tide, increasing accretion once more. Conversely, if sediment supply increases, the elevation of the marsh will increase, decreasing the hydroperiod and reducing the amount of sediment reaching the marsh. In each case, the equilibrium elevation of the marsh will reflect the supply of sediment, with lower marshes characteristic of less sediment input relative to higher marshes.

Of course, it is not always possible for marsh accretion to keep up with accelerated sea level rise, enhanced subsidence or a decreased sediment load if the combined increase in inorganic deposition is ultimately insufficient or if the enhanced stress of inundation on marsh vegetation is too great. In this regard, marshes dominated by allochthonous inorganic sediment may be sensitive to the generally decreasing discharge of fine sediment to the coastal ocean (STEVENSON *et al.*, 1988). Resulting patterns of marsh degradation are discussed further in a later section of the paper.

Spatial Patterns in Morphodynamic Feedback

If hydroperiod were the only factor determining accretion throughout a given marsh, then an eventual flattening of the marsh surface could be expected with time (PETHICK, 1984). However, proximity to sediment source can also be expected to play a fundamental role in determining spatial patterns in equilibrium marsh elevation (STODDART *et al.*, 1989; FRENCH and SPENCER, 1993; FRENCH *et al.*, 1995; LEONARD, 1997). As sediment collects in areas nearest to the source of flow into the marsh, such as levees, these areas will accrete, rising in elevation, and decreasing their local duration of inundation. This, in turn, will cause more sediment to bypass these high areas via lower lying creek headwaters, depositing more sediment at lower elevations further away from the sediment source, especially local lows in the interior (LEONARD, 1997). However, accretion near tidal creeks will still be favored because of higher sediment concentrations (FRENCH and SPENCER, 1993). So a marsh surface dominated by tidal deposition of inorganic sediment will ultimately be characterized by spatially uniform accretion only if areas of the marsh further from the source of sediment laden water are lower in elevation and areas closer to the source are higher. The overall rate of sedimentation in both locations can then be equal, since higher concentrations are paired with shorter inundation durations nearer the source of flow onto the marsh, and lower concentrations are paired with longer durations of inundation farther from the source of sediment.

Lower marsh elevations farther from the seaward edge of a tidal embayment can be caused by the influence of the marsh-channel system itself on high water levels (VAN DER MOLEN, 1997). In relatively large, highly frictional tidal embayments, high water elevation decreases significantly with distance into the system (FRIEDRICHS and MADSEN, 1992). Thus the absolute elevation of the equilibrium marsh surface will decrease with landward distance into the embayments because the absolute elevation of high water similarly decreases.

HYDROPERIOD AND ACCRETION OF ORGANIC MATTER

Decreasing Hydroperiod

In contrast to the stabilizing morphodynamic feedback of hydroperiod on accretion of allochthonous sediment, decreased hydroperiod favors increased vegetative growth, enhanced accretion of organic matter, and a further shortening of the hydroperiod (REED, 1990, Figure 16). Since physical stress on vegetation generally decreases with reduced inundation, natural grass density generally increases with elevation (PETHICK, 1984; DELAUNE *et al.*, 1990; DE LEEUW and BUTH, 1991; NYMAN *et al.*, 1993, 1995b). Greater grass density provides more above and below ground *in situ* organic matter to potentially contribute to accretion (CALLAWAY *et al.*, 1996; DAY *et al.*, 1999) and also enhances trapping of sediment and organic detritus. For example, grass density on the Gulf coast is species specific, with *Spartina patens* and *Juncus roemerianus* found in thicker stands than *Spartina alterniflora* (NYMAN *et al.*, 1995a). Enhanced sediment trapping by the thicker growing species then contributes to formation of higher marsh zones less prone to waterlogging (NYMAN *et al.*, 1995a). In addition, *Spartina patens* is more resistant to decomposition than *Spartina alterniflora*, which further enhances accretion (NYMAN *et al.*, 1995b).

Increasing Hydroperiod

If future sea level rise is greater than the present rate of accretion in tidal marshes dominated by organic matter (i.e., hydroperiod increases), such marshes may have a harder time keeping up with accelerated sea level rise than will marshes dominated by inorganic sediment (BRICKER-URSO *et al.*, 1989; CALLAWAY *et al.*, 1997). This conclusion follows logically from the observation that increased inundation and associated salt stress tend to reduce grass productivity and resulting organic matter accumulation (NYMAN *et al.*, 1993; BOESCH *et al.*, 1994). In many Gulf coast marshes, for example, variation in vertical accretion is due primarily to variations in organic matter accumulation rather than mineral matter accumulation (NYMAN *et al.*, 1993; CALLAWAY *et al.*, 1997, Figure 17). Inadequate accretion relative to sea level rise in these marshes is the result of inadequate plant production which, in turn, results from the stresses of extended inundation (NYMAN *et al.*, 1993; BOESCH *et al.*, 1994; CALLAWAY *et al.*, 1996; DAY *et al.*, 1999). Thus increased hydroperiod favors decreased vegetative growth, decreased accretion of organic matter, and a further lengthening of the hydroperiod.

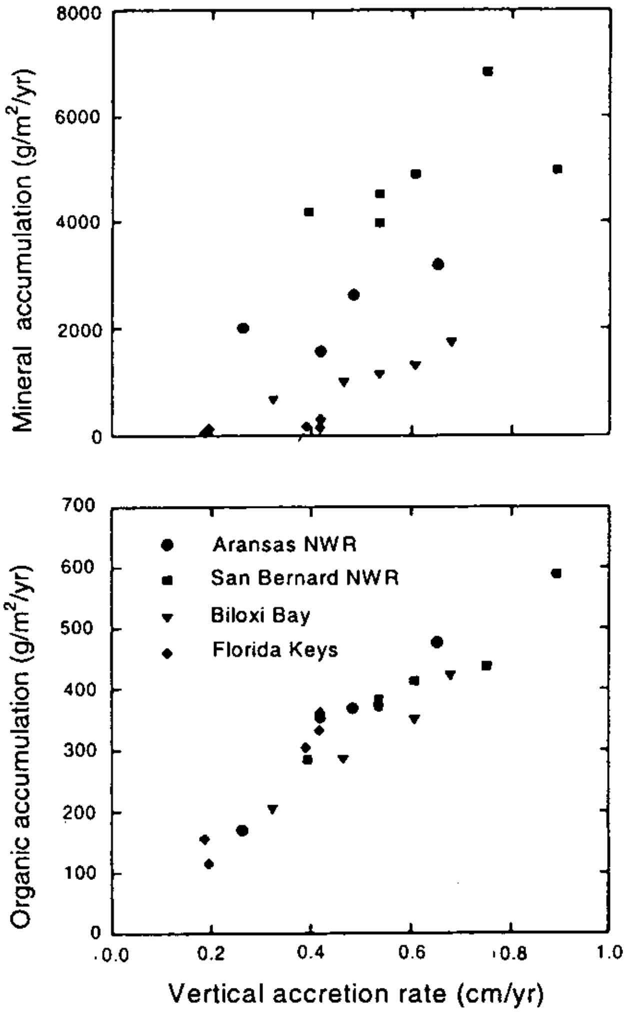

Figure 17. Correlation of vertical accretion rates with mineral accumulations rates (top) and organic accumulation rates (bottom) for all cores collected in four coastal wetlands along the U.S. Gulf coast. Accumulation rates are based on accretion since the 1963 peak in bomb-derived ^{137}Cs. From Callaway *et al.* (1997), published with permission of *Progress in Physical Geography*.

Confounding Factors

The above generalizations may be somewhat simplistic. For example, organic rich marsh soils are more affected by compaction, reducing long-term accretion (PETHICK, 1984; CAHOON *et al.*, 1995), and decreasing the likelihood of "run away" accretion of organic matter. Also, the inverse correlation between inundation and productivity is not universal. Some Gulf coast marshes appear to favor more rapid accumulation of *in situ* organic matter on lower areas of the marsh (CALLAWAY *et al.*, 1997), perhaps because greater soil water movement and better drainage there supports more grass production. Furthermore, grass production and *in situ* organic matter preservation are not necessarily correlated. Good drainage favors production, but it also favors more rapid decomposition because of increased aerobic decomposition rates (HEMMINGA *et al.*, 1988). In addition, total inorganic and organic accumulation rates may be correlated within a given marsh. Plant production has been observed to increase with greater soil mineral content because of benefits associated with iron availability, favorable cation exchange, and increased soil bulk density (BRICKER-URSO *et al.*, 1989; NYMAN *et al.*, 1993).

Regional variations in marsh species and climate also play important roles in the preservation of *in situ* organic matter. The roots of native New England salt marsh grasses are especially resistant to degradation, which partially explains the accretion of up to 90% organic matter on these marshes and a preponderance toward vast areas of high marsh (FREY and BASAN, 1985). In contrast, U.K. and Dutch marshes accrete virtually no organic matter in their soils, in part due to the low potential for root preservation among the locally dominant varieties of marsh grass (HEMMINGA and BUTH, 1991; EISMA and DIJKEMA, 1997). Perhaps an abundance of fine sediment available to North Sea marshes has meant less pressure to naturally select species adapted for root preservation. Preservation is also sensitive to climate, with warmer temperatures favoring more rapid decomposition (FREY and BASAN, 1985; STEVENSON *et al.*, 1988). This may help explain the low percentage of organic matter preserved in generally low-lying Georgia marshes relative to New England marshes.

MARSH DEGRADATION

Physical Erosion

Because of the extreme damping of flow through marshes, it is probably unlikely that water flow through healthy marsh grass ever results in long-term net erosion of sediment from the marsh surface (FREY and BASAN, 1985). Even extreme storm surges which allow wave action to directly disturb the marsh surface do not appear cause long term surface erosion in natural marshes at a rate faster than subsequent, more regular inundation can restore (FREY and BASAN, 1985; PETHICK, 1992). Overall, direct erosion is much more likely to occur on channel banks where tidal currents can undermine the marsh, creating slumps along the banks (ALLEN, 1997), or along the seaward or bay-side edges of fringing marshes where wind waves can directly attack the marsh (FINKELSTEIN and HARDAWAY, 1988; PETHICK and REED, 1988; DE JONG *et al.*, 1994). At high latitudes, ice floes tear out marsh clumps and can represent an important component of the sedimentary budget (DIONNE, 1989). The result is often formation of marsh "cliffs" where a break in topography is formed that is apparently too large for subsequent marsh colonization (PETHICK, 1992). Much of the material eroded by wave action at the seaward edge of a marsh can be expected to be redeposited on the marsh surface immediately landward of the eroding edge, helping to maintain the marsh surface with respect to rising sea level (PETHICK and REED, 1988; STEVENSON *et al.*, 1988).

It is interesting to consider how a marsh may maintain its surface area in response to continual long term erosion at its edges. Sea level rise may allow a marsh to expand landward at a rate about equal to seaward erosion, as is occurring in some marshes in Virginia (KASTLER and WIBERG, 1996). A corollary to this is that retreating marshes backed by seawalls or bulkheads are doomed to shrink (REED, 1988; FRENCH, 1991). Sometimes the collection of sediment at the base of the cliffs leads to new seaward growth of a secondary marsh on a lower terrace (REDFIELD, 1972; ALLEN, 1989; PETHICK, 1992). Alternatively, the seaward edge of the marsh may become highly dissected in a manner which effectively dissipates waves, minimizing further erosion (PETHICK, 1992). Marsh surface area may also be maintained if compression brought about by accretion within the marsh continually forces sediments forward along the cliff edge (REDFIELD, 1972; PETHICK, 1992).

Waterlogging

Long-term submergence can prevent sufficient oxygen from reaching the roots of salt marsh grasses such as *Spartina alterniflora* (REDFIELD, 1972). In waterlogged marsh soils, a gradient in the redox potential is observed between streamside and inland marshes (DELAUNE *et al.*, 1983; REED, 1990). Also, soil waterlogging may prevent adequate nitrogen uptake by plants and induce sulfide toxicity (MENDELSSOHN and MCKEE, 1988; REED, 1990; BOESCH *et al.*, 1994). Associated saline intrusion can lead to large-scale shifts in marsh species with associated loss of elevation as fresher water species die back and intrusion of sulfate rich water stimulates more rapid decay of organic matter (BOESCH *et al.*, 1994; DAY *et al.*, 2000). Waterlogging instigates the detrimental feedback loop discussed in the previous section where inadequate plant growth limits vertical accretion, which further increases flooding and decreases plant production (NYMAN *et al.*, 1993). In contrast to wave erosion along the edge of a marsh, the first areas to degrade from waterlogging are the central portions of the marsh relatively removed from tidal channels and from access to inorganic sediment. Waterlogging can be triggered by sea level rise, subsidence and/or reduced sediment supply. This form of degradation is particularly evident along the salt marshes of the Mississippi delta, where a decrease in river sediment supply since the mid-19th century associated with dam construction, channelization of streams and rivers, and construction of canals has critically reduced the net accretion rate within the central portions of many marshes (WELLS and COLEMAN, 1987, see Figure 1; KESEL, 1988; EVERS *et al.*, 1992; NYMAN *et al.*, 1993; BRITSCH and DUNBAR, 1993; BOESCH *et al.*, 1994; BASS and TURNER, 1997).

More localized areas of waterlogging within otherwise healthy marshes can form isolated salt pans or "pond holes" (REDFIELD, 1972; PETHICK, 1984). Inadequate local drainage creates standing water which causes vegetation to deteriorate. Concentration of salt by evaporation may further accelerate the death of the vegetation and prevent later recolonization. Salt pans can form from the blocking of marsh creeks by slumping of the bank, retention of water, and subsequent enlargement by decomposition of the surrounding marsh. They may also be the result of small areas left unvegetated when the marsh first formed.

Impact of Dredging

Construction of canals in Louisiana salt marshes has been associated with the an acceleration of marsh loss (STEVENSON *et al.*, 1988; TURNER and RAO, 1990, Figure 18; EVERS *et al.*, 1992; BOESCH *et al.*, 1994; BASS and TURNER, 1997). Yet some canals in Gulf Coast marshes do not appear to be associated with less marsh sedimentation relative to natural creeks (CAHOON and TURNER, 1989; DELAUNE *et al.*, 1989; DAY *et al.*, 2000). The key factor causing the detrimental influence of canals is probably the associated impact of traditional channel dredging practices (BRITSCH and DUNBAR 1993; TURNER, 1997). Dredging decreases velocity in artificial canals or natural creeks, increasing the likelihood that sediment will settle in the channel and never make it to the marsh (WANG *et al.*, 1994; WANG, 1997). The dropping out of suspended sediment in the dredged channels significantly lowers the suspended sediment concentrations otherwise maintained by tidal or surge-induced flow associated with a given water elevation (WANG, 1997). Also, dredge disposal in isolated spoil banks adjacent to canals removes sediment from the marsh entirely and may physically block sediment laden flow from reaching the marsh (TURNER and RAO, 1990; EVERS *et al.*, 1992; BASS and TURNER, 1997). Dredging of canals perpendicular to the shoreline may accelerate detrimental saline intrusion

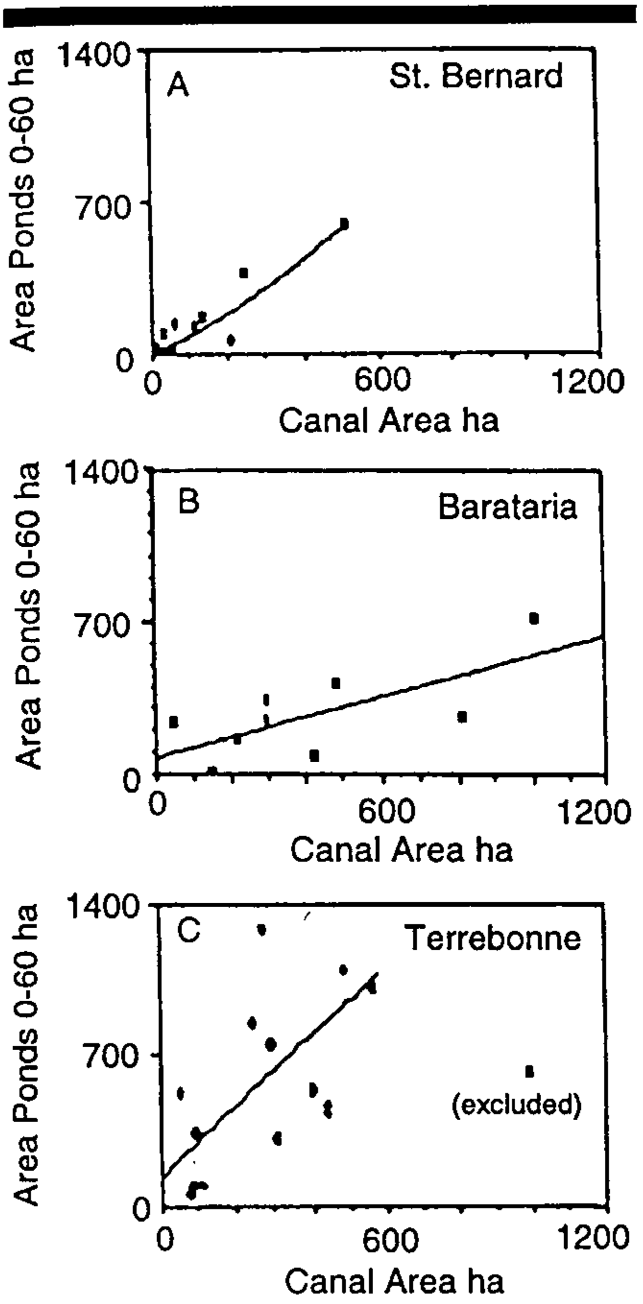

Figure 18. The relationship between the net gain in ponds < 60 ha formed between 1955-56 and 1978 and canal surface area (ha) for three marshes on the Mississippi delta. From Turner and Rao (1990), published with permission of *Estuaries*.

into brackish water marshes (BOESCH *et al.*, 1994). On the other hand, if canals have cross-sectional areas close to equilibrium with the tidal or storm surge discharge they carry, they should work much like natural tidal creeks and tend to act as a conduits for more effective delivery of allochthonous sediment to the marsh. Furthermore, thin-layer deposition of dredged material on marshes can enhance net accretion and help maintain marsh elevation (FORD *et al.*, 1999).

VARIATIONS IN MARSH RESPONSE AS A FUNCTION OF TIDAL RANGE

Macrotidal Marshes

The relative role of tides and storm surges in salt marsh accretion varies markedly as a function of tidal range. In macrotidal marshes (spring tidal range > 4 m), tides alone are most likely to provide sufficient sediment to maintain a stable equilibrium elevation with respect to sea level rise (FRENCH and SPENCER, 1993). This is because the very regular, extensive flooding of the marsh which occurs with every spring tide is by far the dominant mode of sediment delivery to the marsh. Unless storm surges hit at spring high tide, the extra one or two meters of flooding associated with a typical storm surge will have a small impact on the overall duration and frequency of flooding over the majority of the marsh. All else being equal, macro- and mesotidal coasts are also more favorable environments for the development of extensive tidal salt marshes than are microtidal coasts (HAYES, 1979; OERTEL *et al.*, 1992). This is because the area most favorable to marsh growth, namely that between neap and spring high water, logically grows with tidal range. Nonetheless, it is not clear that within meso- to macrotidal environments marsh accretion rates simply increase directly with tidal range. Data from North Sea marshes suggest that overall sedimentary status has less to do with tidal range than the interaction between the magnitude of sediment input and external sea-level forcing (FRENCH, 1994).

The larger the tidal range, the more likely occasional intense storms are to be erosional rather than accretionary (PETHICK, 1992). This is because a significant storm surge hitting at spring high tide in a macrotidal system necessarily produces water several meters deep over the lower intertidal area, allowing quite large waves to impinge directly on the salt marsh. The surfaces of salt marshes along the macrotidal Essex coast of Great Britain have been shown to be subject to widespread erosion in concert with deposition on adjacent intertidal flats. This erosion is in response to individual winter storm surges associated with wave heights of one to several meters impinging on the marsh edge (PETHICK, 1992, Figure 19). Within several months to a few years, tidal action had returned the eroded sediment to the marsh once more.

Mesotidal Marshes

Storm surges have also been associated with net export of sediment in some mesotidal marsh systems in Georgia (FREY and BASAN, 1985) and South Carolina (WOLAVER *et al.*, 1988a), but to a lesser extent than in macrotidal sys-

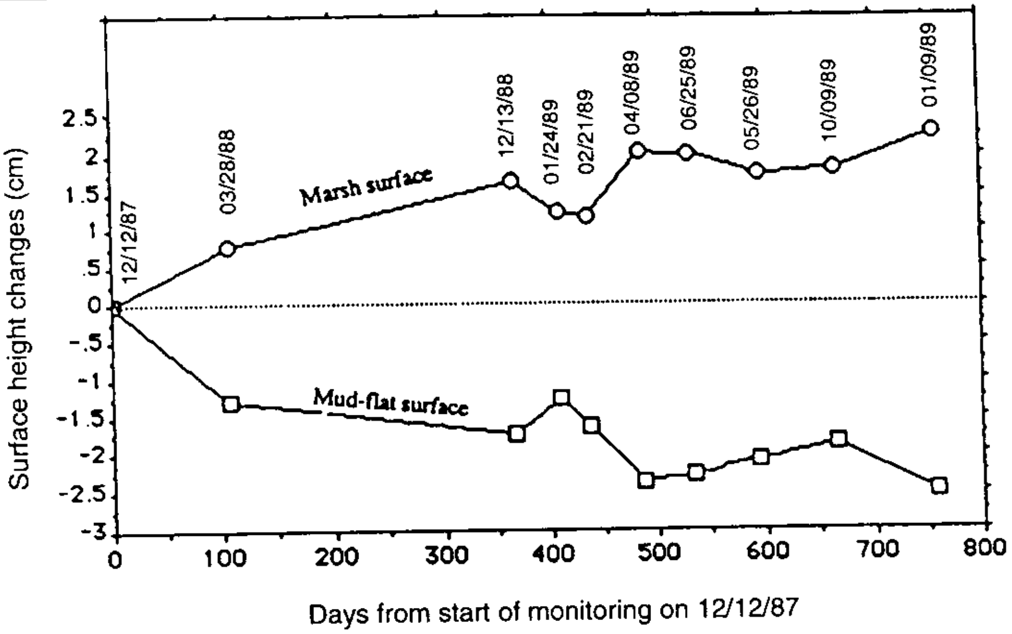

Figure 19. Vertical changes in surface height on an open coast marsh and adjacent tidal flat, Dengie Peninsula, Essex, U.K. Note effect of major easterly storms from 12/13/88 to 2/12/89. From Pethick (1992), published with permission of *Cambridge University Press*.

tems. In other mesotidal systems, such as San Francisco Bay (DeLaune and Patrick, 1990), storm surges are a source of net deposition. As tidal range decreases, storm surges play a role increasingly analogous to the spring tide in a macrotidal environment. During storm surges in meso- and microtidal marshes, depths over the lower intertidal areas are generally too small to allow significant wind waves to impinge on the marsh surface, which limits wave-induced erosion. The higher velocities over the marsh during surges allow sediment to move more quickly to the upper marsh, and the extended duration allows the sediment to more completely settle out.

A correlation has been reported between tidal range and net accretion rate among meso- and microtidal marshes (Harrison and Bloom, 1977; Stevenson *et al.*, 1986, Figure 20). Among marshes which are "catching up" with a recent acceleration in the rate of sea level rise, it makes sense that systems with higher tidal ranges will deposit more marine sediment on the marsh surface. Friedrichs (1995) has shown that tidal creek velocity tends to increase with tidal range. This will set a higher background concentration for the sediment "source" at the edge of the marsh. Also, as tidal range increases, the general tendency toward flood-dominance increases (see following sections), which further increases the likelihood of high sediment concentrations in the marsh channels. The above arguments apply only for marshes dominated by allochthonous sediment, and there is no reason to expect similar patterns in marshes dominated by *in situ* organic matter. Investigators working in systems dominated by *in situ* organic matter, such as some Gulf Coast

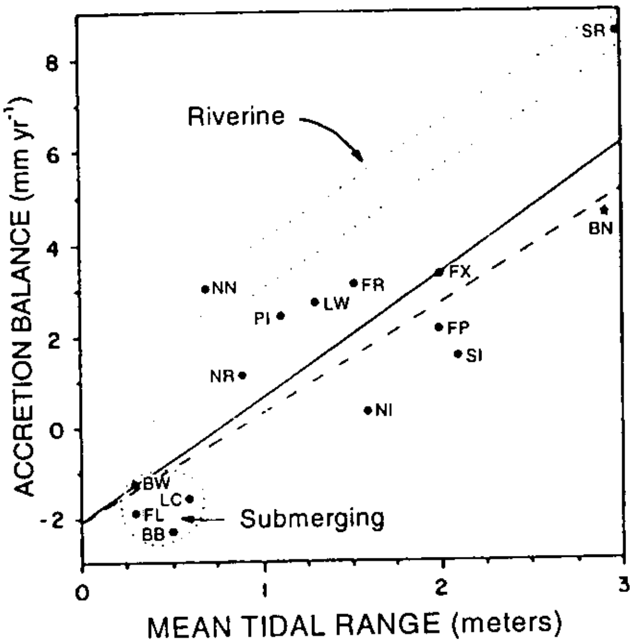

Figure 20. Relationship between net accretion (vertical accretion rate minus local sea level changes recorded by tide gauges) and mean tidal range of U.S. marshes. Solid regression line is for all 15 marshes, while dashed line is for 13 non-riverine marshes. From Stevenson *et al.* (1986), published with permission of *Academic Press*.

marshes (CALLAWAY *et al.*, 1997) or northern New England marshes (KELLEY *et al.*, 1988) have indeed found there to be no significant relationship or even a negative relationship between tide range and accretion rate.

Microtidal Marshes

In regions of smaller tide range, such as the U.S. Gulf coast and the Mediterranean, wind-driven storm surges (or river floods in the vicinity of deltas) are a more important source than tides for delivering sediment to the marsh (WELLS and COLEMAN, 1987; REJMANEK *et al.*, 1988; REED, 1989; CHILDERS and DAY, 1990; NYMAN *et al.*, 1993, 1995a; DAY *et al.*, 1995, 1999; CAHOON *et al.*, 1996; HENSEL *et al.*, 1999). In microtidal systems, storms do not appear to commonly result in net erosion of the marsh surface. Depths over the lower intertidal area are generally too shallow during storms in microtidal marsh systems to allow significant wind waves to impinge directly on the marsh surface. Rather, storms are associated with accelerated deposition on the marsh through a combination of increased duration of inundation and increased sediment concentration in the water entering the marsh (CAHOON and REED, 1995; LEONARD *et al.*, 1995a, Figure 21; LEONARD *et al.*, 1995b). Thus it is not surprising that efforts to reduce storm flooding in managed microtidal marshes have led to reduced accretion rates relative to unmanaged sites (BOUMANS and DAY, 1994). Deposits associated with major storms tend to have significantly lower organic content than deposits between storms and may lay down the equivalent of several years' worth of non-storm deposition (GOODBRED and HINES, 1995; NYMAN *et al.*, 1995a) . Because the storm surges which deliver the majority of allochthonous sediment to microtidal marshes tend to submerge the entire marsh for extended periods, tidal channels are relatively less important in determining deposition in such systems. Thus microtidal marsh sediments are more likely to be deposited in bands paralleling the general outline of the marsh.

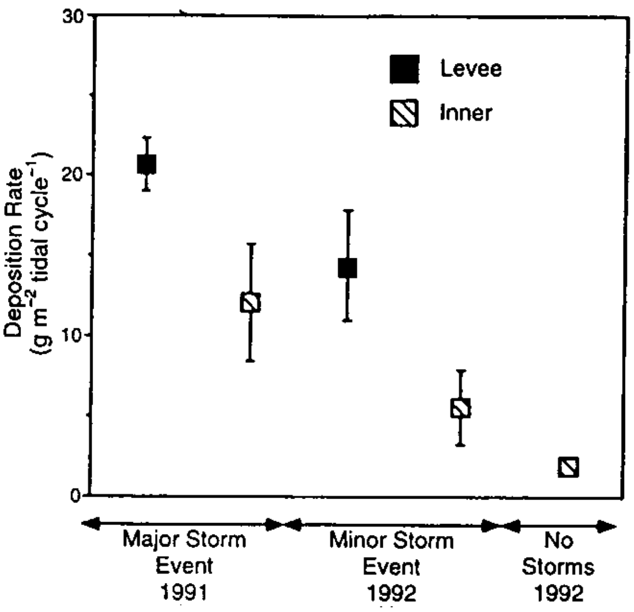

Figure 21. Deposition rates determined from surface trap data on levee and inner marsh sites for winter deployments in a *Juncus roemerianus* marsh near Cedar Creek, Florida. Levee traps were not recovered for the non-storm period of 1992. Leonard *et al.* (1995a), published with permission of *Journal of Coastal Research*.

Microtidal systems are the most sensitive to perturbations in sea level and suspended sediment concentration because they are the least able to adjust by changing their mean elevation with respect to the tide (DAY *et al.*, 1995). A relatively small increase in sea level or decrease in accretion rate can submerge the marsh vegetation to such a degree that the environment is too stressful for the grass to survive. Conversely, when accretionary conditions are favorable, microtidal marshes can be expected to build seaward more quickly than systems in higher tide ranges. This is because it takes relatively little upward growth to significantly reduce the duration and frequency of submersion, causing available suspended sediment to be deposited further seaward. The potential for massive marsh expansion in such systems in the presence of plentiful sediment is highlighted by the historical studies of WELLS and COLEMAN (1987, Figure 1) which documented horizontal marsh expansion rates of hundreds of meters per year on the Mississippi Delta, soon followed by equally remarkable marsh loss rates once the sediment supply decreased.

SALT MARSH CREEK MORPHODYNAMICS

Creek Formation and Vegetation

Marsh vegetation strongly resists wholesale lateral displacement (VAN EERDT, 1985; REED, 1990). Therefore, the locations of major channels in many if not most natural salt marshes are initially inherited (EISMA, 1997), either from terrestrial drainage (GARDNER and BOHN, 1980; KNIGHTON *et al.*, 1992; KELLEY *et al.*, 1995), constraints of underlying bedrock (LEONARD *et al.*, 1995a), or from tidal channels previously incised in tidal flats or shallow lagoons (REDFIELD, 1972). Vegetation also causes tidal channels in salt marshes to be narrower and deeper than channels on tidal flats (EISMA, 1997). With time, undercutting and slumping favors the formation and amplification of meanders in salt marshes, while the presence of vegetation and resilience of slump blocks simultaneously resists meander migration (GABET, 1998). The cohesiveness and high resistance of tidal channel banks due to salt marsh vegetation appears to allow excessively tight meander bends to be the norm, more so than in alluvial systems (ASHLEY and ZEFF, 1988), fresh water marshes or tidal flats (EISMA, 1997). Meanders are more stable in more thickly vegetated marshes such as those in New England relative to less thickly vegetated marshes such as those in Georgia (REDFIELD, 1972).

The density of minor marsh creek channels is thought to be determined in large part by the tidal prism such that the creek density is just sufficient to accommodate the "hydraulic duty" of the marsh platform (ALLEN, 1997). If there are too many minor creeks relative to the tidal prism, small creeks will close via headward retreat, bank collapse, silting up, and vegetation in-filling or pan formation. Minor creek formation via headward erosion allows a dynamic equilibrium to be maintained (FRENCH and STODDART, 1992; ALLEN, 1997). New channels have also been observed to form by the reconnection of salt pans (PERILLO *et al.*, 1996). The smallest creeks are generally the most dynamic, with the rate of migration and cross-sectional evolution decreasing with channel size.

Equilibrium Cross-Section

Unlike the marsh surface, marsh channels are submerged most of the time, and duration of inundation is not the most critical parameter governing sediment deposition. Instead, maximum tidal velocity is thought to be a more relevant property (HUME, 1991; VAN DONGEREN and DE VRIEND, 1994; FRIEDRICHS, 1995). If tidal velocity is larger than some critical value, then excess shear stress will cause erosion to deepen the channel. Conversely, if velocity is below some critical value, deposition will cause the channel to shoal. This tendency leads to a stabilizing feedback mechanism which causes marsh creek cross-sectional area (*A*) to rapidly approach a predictable equilibrium size which is a function of peak tidal discharge (*Q*). Peak discharge itself does not change rapidly with channel shoaling or erosion because *Q* is primarily a function of intertidal storage on the adjacent marsh surface, not primarily a function of the local channel cross-section. Marsh tidal channels respond much more quickly toward equilibrium than the marsh surface itself, generally over time scales of months to years rather than decades.

FRIEDRICHS (1995) defined the stability shear stress, τ_S, necessary to maintain zero net erosion or deposition in equilibrium estuarine and marsh tidal channels. FRIEDRICHS (1995) argued that if bed shear stress (τ) is greater than τ_S, net erosion will occur, increasing *A*, and reducing $\tau \sim (Q/A)^2$ back toward τ_S. If $\tau < \tau_S$, there will be net deposition, reducing *A* and increasing τ toward τ_S. FRIEDRICHS (1995) estimated *Q* and *A* at 242 cross-sections in 26 separate tidal channel systems, all of them within estuaries or marshes sheltered from the confining effects of wave-induced littoral drift. Assuming a single value of τ_S characterizes the entire length of a given tidal channel, open channel flow theory predicts that along-channel geometry will follow the relation

$$Ah^{1/6} \sim Qn\left(\frac{\rho g}{\tau_s}\right)^{1/2} \qquad (1)$$

where *h* is channel depth, *n* is Manning's friction coefficient, ρ is fluid density, and *g* is the acceleration of gravity. Along-channel regressions of the form $Ah^{1/6} \sim Q^{\beta}$ give a mean observed value for β of 1.00±0.06, which is consistent with this concept (FRIEDRICHS, 1995, Figure 22). Results indicate that a lower bound on τ_S (and an upper bound on *A*) for stable tidal channels is provided by the critical shear stress ($\tau_C \approx 0.6$ Pascals) just capable of initiating sediment motion. Observed τ_S (proportional to velocity squared) is found to vary among all systems as a function of spring tidal range (*R*, in meters) according to the relation $\tau_S \approx 2.3\,R^{0.79}\,\tau_C$.

Creek Evolution

Changes in marsh creek geometry during the evolution of a marsh depend mainly on the evolution of the upstream tidal prism during that period (GARDNER and BOHN, 1980; ALLEN, 1997). If the marsh expands seaward under stable sea level conditions while the elevation of

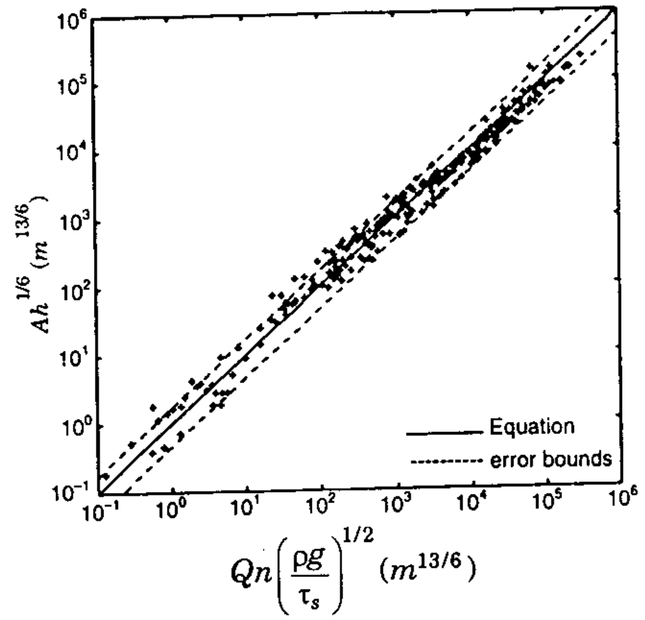

Figure 22. Observations of the cross-sectional parameter $Ah^{1/6}$ for 236 sections from 25 natural marsh, estuary or tidal inlet systems (all sheltered from ocean waves) as a function of peak spring discharge, stability shear stress, and other externally fixed variables, superimposed on the 1:1 line given by the equation in the text. From Friedrichs (1995), published with permission of *Journal of Coastal Research*.

the upstream marsh likewise stays constant with respect to the tide, then the upstream tidal prism will not change and there is no reason for the upstream channel geometry to fundamentally change (REDFIELD, 1972). If, however, the marsh transgresses landward as sea level rises, the upstream prism will increase, and channel cross-sections will necessarily grow (GARDNER and BOHN, 1980; KELLEY *et al.*, 1995; ALLEN, 1997; DAY *et al.*, 1999). As the prism increases at any one location, the local density of marsh creeks will increase due to tributary addition and the headward growth of first-order creeks. The opposite will occur during a regression: with time, the local upstream prism will be reduced, and channels will in-fill or be blocked by slumps and be deserted (FRENCH and STODDART, 1992; ALLEN, 1997). If, during a short-term regression, major creek channels become fresh water streams, or if sea level change is gradual, then major channels are likely to be preserved more or less in place (GARDNER and BOHN, 1980; ALLEN, 1997). If the sea level varies in steps, however, ALLEN (1997) argues that tidal creek networks are unlikely to be inherited from one cycle to the next.

TIDAL ASYMMETRY AND ITS RELEVANCE TO TIDAL MARSHES

Impact of Flood- or Ebb-Dominance on Marsh Elevation

A flood-dominant tide is one which has stronger peak currents during flood than during ebb. Conversely, an ebb-dominant tide has stronger peak currents during ebb. Because sediment erosion and transport are geometrically related to velocity, flood-dominant tides in salt marsh creeks tend to move sediment landward even though the definition of flood dominance requires no net movement of water (AUBREY, 1986; VAN DE KREEKE and ROBACZEWSKA, 1993; FRIEDRICHS *et al.*, 1998). Likewise, ebb-dominant tides tend to move sediment seaward. Most British embayments and estuaries containing salt marsh are characterized by flood-dominant tides (ALLEN and PYE, 1992) as are most inlet/marsh channels in New England (FRIEDRICHS and AUBREY, 1988; LINCOLN and FITZGERALD, 1988; STEVENSON *et al.*, 1988) and southern California (FREY and BASAN, 1985). Ebb-dominant tides are characteristic of marsh creeks in Georgia (FREY and BASAN, 1985; ZARILLO, 1985) and South Carolina (FRIEDRICHS and AUBREY, 1988; STEVENSON *et al.*, 1988). Of course exceptions inevitably occur in each region, such as ebb-dominant marsh creeks in North Norfolk, U.K. (FRENCH and STODDART, 1992) and flood-dominant channels in Little River, S.C. (FRIEDRICHS and AUBREY, 1988).

The tendency of flood-dominant currents to transport marine sediment landward toward first-order marsh creeks increases the average suspended sediment concentration at the creek/marsh boundary and therefore increases the supply of marine sediment to the marsh (STEVENSON *et al.*, 1988; LEONARD *et al.*, 1995b). As discussed earlier, an increase in sediment supply to the marsh causes the marsh to accrete to a higher level until a decreased inundation frequency reduces net deposition once more. Thus flood dominant tidal channels can be expected to be associated with relatively high marsh when at equilibrium with relative sea level. Conversely, ebb-dominant currents will tend to transport marine sediment seaward, reduce the supply of sediment to the marsh (STEVENSON *et al.*, 1988) and logically favor relatively lower marsh at equilibrium. This may be another reason why tidal embayments in New England, which tend to be flood dominant, have more high marsh than tidal embayments in Georgia (FREY and BASAN, 1985), which tend to be ebb dominant. Ebb dominance may also contribute to the small amount of organic matter preserved in ebb dominant marshes, such as those in South Carolina and Georgia (STEVENSON *et al.*, 1988). However, predominantly ebb directed transport of detritus was found to be a negligible loss term for organic matter relative to decay in a mineralogically dominated marsh in the Netherlands (HEMMINGA *et al.*, 1996).

Morphologic Controls on Flood- or Ebb-Dominance

In a series of articles, Friedrichs and others (FRIEDRICHS and AUBREY, 1988, 1994; FRIEDRICHS *et al.*, 1992; FRIEDRICHS and MADSEN, 1992; FRIEDRICHS *et al.*, 1998) have investigated the morphological properties of tidal embayments which control flood- and ebb-dominance. By assuming momentum is confined to the creek and the intertidal marsh acts in storage capacity only, the propagation speed for the tidal wave can be shown analytically to increase with the channel depth and decrease with the width of the submerged intertidal storage area (Friedrichs and AUBREY, 1994). If a channel is shallow relative to its tidal range and drains a relatively small intertidal area, then the tidal wave speed will be faster around high tide than around low tide. High tide will propagate to inner areas of the marsh more quickly than low tide, and the duration of the rising tide will be shorter than the duration of the falling tide. Since the same amount of water enters on the rising flood as on the falling ebb, the flood will tend to be stronger than the ebb and the tidal creek will be flood dominant (AUBREY and SPEER, 1985, Figure 23). If a channel is deep and drains a large intertidal area, then the tidal wave will move faster around low tide. The duration of the falling tide in the inner marsh will be shorter, and the tidal creek will be ebb dominant. The correspondence between duration asymmetries and flood- versus ebb-dominance is not exact. As the ebb-to-flood duration ratio grows from much less than one to close to one, ebb-dominance usually begins somewhat before a duration ratio of one is exceeded (FRENCH and STODDART, 1992; LESSA, 1996).

To a first approximation, the critical morphological criteria distinguishing ebb- and flood-dominant tidal creek systems is given by the tidal asymmetry factor (FRIEDRICHS and AUBREY, 1994, Figure 24):

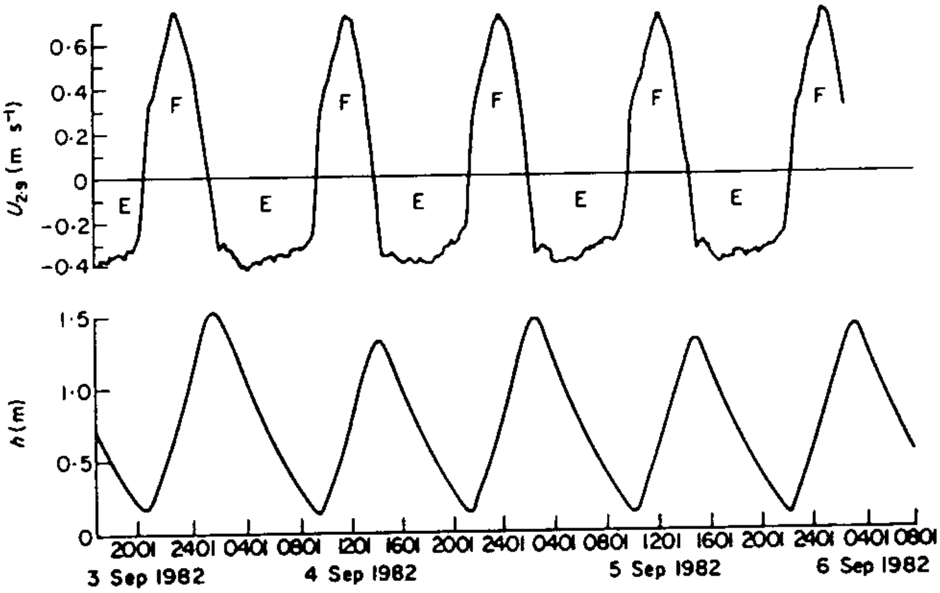

Figure 23. Velocity (top panel, measured 2.9 m above bottom in 3.5 m water depth) and sea surface elevation, showing the characteristic distortion of the tide within a tidal channel at the Nauset Inlet marsh, Massachusetts, USA. F = flood; E = ebb. From Aubrey and Speer (1985), published with permission of *Estuarine Coastal and Shelf Science*.

$$\gamma = \delta \frac{\Delta h}{\bar{h}} - \frac{\Delta b}{\bar{b}} \qquad (2)$$

where $\bar{h}$ and $\bar{b}$ are channel depth and embayment width (each averaged in time and space), Δh and Δb are the amplitude of depth and width variation over the tidal cycle, respectively, and δ varies between 1 and 2 depending on the degree to which friction dominates the momentum equation (2 = strongly frictional). If γ is positive, the channels are shallow, the intertidal area is small, and the creek system is flood dominant. If γ is negative, the channels are deep, the intertidal area is large, and the creek system is ebb dominant. Based on $\Delta h/\bar{h}$, the equation for γ suggests that macrotidal embayments will tend to have flood-dominant channels (and a higher equilibrium marsh), while microtidal embayments will tend to have ebb-dominant channels (and a lower equilibrium marsh). Offshore tidal asymmetry can also contribute to flood- or ebb-dominance within a marsh (PETHICK, 1980). For example, the tides offshore of The Netherlands tend to be faster rising, which further favors flood-dominance within Dutch marsh channels (DRONKERS, 1986a).

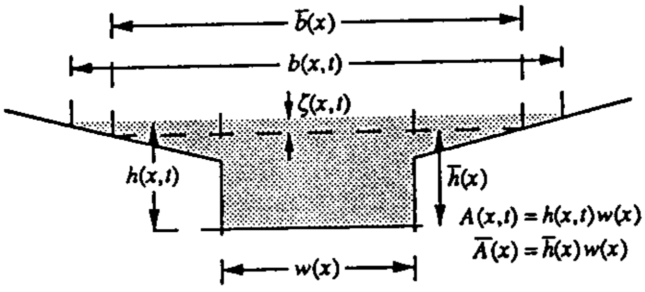

Figure 24. Diagram of an idealized tidal embayment cross section: b is total embayment width (including intertidal storage in tidal flats or marsh), ζ is tidal elevation, h is cross-sectionally averaged channel depth, w is channel width (which is equal to embayment width at low tide), and A is channel cross-sectional area. Overbars indicate time averages. From Friedrichs and Aubrey (1994), published with permission of *Journal of Geophysical Research*.

The above results are based largely on modeling of systems with intertidal storage on both tidal flats and marsh such that the addition of water from areas of intertidal storage occurs relatively smoothly between low to high tide. In many tidal marsh systems there is little tidal flat area, and a nearly flat marsh surface causes a sudden transition with tidal height from virtually no marsh to virtually all of the marsh being submerged. In this case the marsh surface acts as a topographic threshold separating two relatively distinct flow regimes (BAYLISS-SMITH *et al.*, 1979, Figure 25; PETHICK 1980; FRENCH and STODDART, 1992; LEONARD, 1997). According to continuity, maximum creek velocities (= Q/A) during both flood and ebb will occur as pulses when the marsh

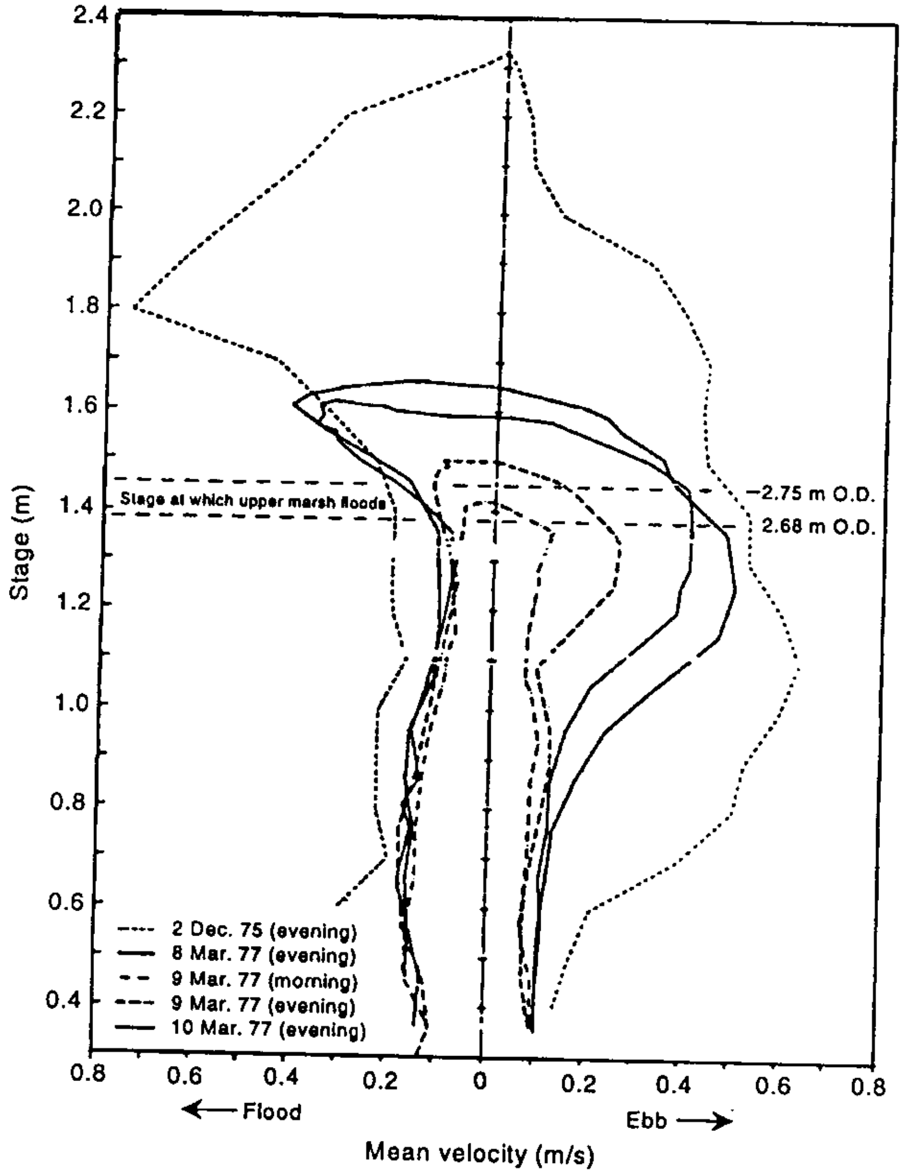

Figure 25. Cross-sectionally averaged velocity as a function of tidal stage for five tides in a minor salt marsh creek on the Upper Marsh at Warham and Stiffkey, north Norfolk, U.K. From Bayliss-Smith *et al.* (1979), published with permission of *Estuarine Coastal and Shelf Science*.

surface is only shallowly flooded, for this is the time when the largest surface area (which determines discharge, Q) is flooded relative to the smallest channel cross-sectional area (A). Nonetheless, determining whether the overall creek velocity will be ebb or flood dominant still requires accounting for the finite time it takes for the tidal wave to propagate through the length of the marsh/creek system, which involves momentum considerations (HEALEY *et al.*, 1981; FRIEDRICHS and MADSEN, 1992; WANG *et al.*, 1999).

Asymmetry Around Slack Water

Another type of asymmetry that causes net sediment transport in tidal creeks is a difference in the rate of current change near high-water slack as compared to low-water slack (DRONKERS, 1986b; RIDDERINKHOF, 1997). If slack around high tide is longer than slack around low tide, more sediment will fall out of suspension after flood relative to ebb, enhancing landward sediment transport and, ultimately, the supply of sediment to the marsh. Tidal embayments with shallow channels and small intertidal flats or marsh favor a longer slack near high water in the channels, because tidal discharge near high water is moving through a larger channel cross-sectional area. This geometry also favors flood-dominance, as discussed above. Thus flood dominance and a longer high water slack often occur together in a given marsh creek system and work together to create relatively high marsh. Embayments with deep channels and extensive intertidal flats and/or marsh favor a shorter slack near high water in the channels, because much more water (associated with the flooded intertidal areas) moves through a relatively unchanged channel cross-sectional area. Since this latter geometry also favors ebb dominance, longer low water slack and ebb dominance work together to favor a relatively low marsh. New England inlet/marsh systems generally fall in the former category, whereas those in Georgia and South Carolina generally fall in the latter.

A similar type of asymmetry can be experienced by suspended sediment particles following a water particle even if the tidal current is entirely undistorted at any one place. If a water parcel containing suspended particles travels during flood through a stretch of channel along which the local amplitude of the tidal current decreases significantly, then the rate of change of current speed experienced by the particles at high water slack will tend to be slower than the rate of change of current speed experienced at low water slack (POSTMA, 1980; VAN DE KREEKE, 1996; EISMA and RIDDERINKHOF, 1997). This will favor enhanced deposition after flood, enhance erosion after ebb, and tend to move sediment landward. Conversely, if the local amplitude of the tidal current increases landward, net sediment transport will be seaward. This general phenomena is also known as scour lag/settling lag (POSTMA 1967, 1980), and it works to ultimately establish the uniform along-channel distribution of stability shear stress discussed earlier (FRIEDRICHS, 1995).

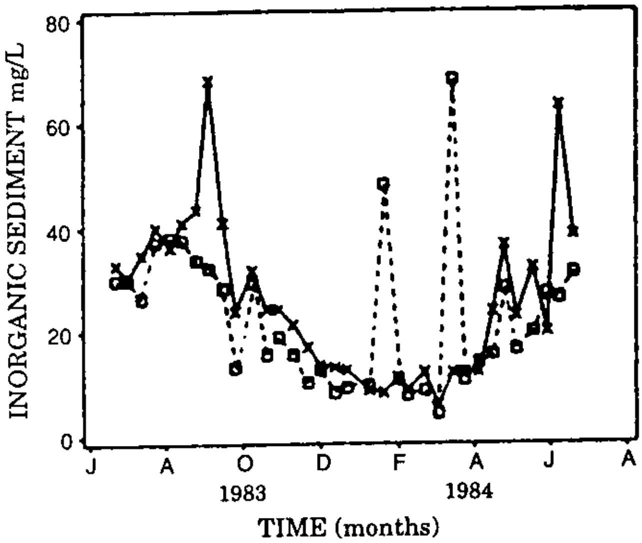

Figure 26. Mean flood and ebb concentrations of inorganic suspended sediments over the course of a year measured at the boundary between Bly Creek and the adjacent *Spartina alterniflora* marsh, North Inlet, SC. Crosses = flood, squares = ebb. From Wolaver *et al.* (1988b), published with permission of *Journal of Coastal Research.*

The above described phenomena of scour/settling lag may be most important in salt marsh systems not along marsh creeks, but rather across the transition from channel to marsh. Scour/settling lag is just another way of characterizing the fundamental mechanism by which marshes trap allochthonous sediment by drastically reducing water velocity. In detecting scour/settling lag from time-series taken at one spot, the most relevant asymmetry is in suspended sediment concentration, not velocity. On the flood, suspended sediment concentration will be higher because the water originates in the channel where resuspension is active. On the ebb, concentration will be lower because water originates in the marsh where virtually no resuspension occurs. This pattern has been observed directly for water moving between tidal creeks and marsh in several tidal embayments (REED, 1988; WOLAVER *et al.*, 1988b, Figure 26; FRENCH and STODDART, 1992; WANG *et al.*, 1993; CHRISTIANSEN *et al.*, 2000).

Spatial and Temporal Variations in Flood- or Ebb-Dominance

Tidal range and tidally-averaged channel depth vary in time over spring-neap cycles and with steric and storm-driven variations in coastal sea level. Also, channel depth generally decreases with distance back into a tidal marsh system. Thus flood versus ebb dominance in a marsh creek system can vary in time and space. In a system with an overall γ value near zero, flood dominance may be favored in the inner marsh creeks if the local $\Delta h/\bar{h}$ value increases landward faster than $\Delta b/\bar{b}$ (FRIEDRICHS *et al.*, 1992). However increased ebb-dominance may also be observed in inner marsh creeks if $\Delta b/\bar{b}$ increases faster (FRENCH and STODDART, 1992). Two-dimensional modeling which does not assume zero momentum over intertidal areas indicates flood dominance is generally favored over the marsh itself (FRIEDRICHS *et al.*, 1992), a result which is in agreement with direct observations (LETZSCH and FREY, 1980).

As tidal range or surge related sea level increases, a system can change its characteristic tidal asymmetry as well. In a system dominated by high marsh, the channels will tend to be flood dominant at neap tide, since little of the total marsh area will generally be flooded. As tidal range increases toward mean conditions, flood dominance may further increase, assuming $\Delta h/\bar{h}$ increases faster than $\Delta b/\bar{b}$ (AUBREY and FRIEDRICHS, 1988). Under a mild storm surge or as spring tide approaches, the marsh may suddenly by overtopped, greatly increasing $\Delta b/\bar{b}$ and shifting flow in the channels toward ebb dominance (FRIEDRICHS *et al.*, 1990; FRENCH and STODDART, 1992; LESSA, 1996). Under an extreme storm surge the system may shift back to flood dominance again (BAYLISS-SMITH, 1979, see Figure 25), because the assumption that momentum is mostly confined to the tidal channels breaks down, and the entire marsh system acts more like one very shallow, very wide channel with a large $\Delta h/\bar{h}$.

MORPHODYNAMIC FEEDBACK ASSOCIATED WITH TIDAL ASYMMETRY

Roles of Channel Depth and Marsh Elevation

There are several ways in which tidal asymmetry creates mechanisms for positive morphodynamic feedback in marsh creek systems (Figure 27). The first group of mechanisms relate to channel depth (FRIEDRICHS *et al.*, 1992). Creek systems characterized by shallow channels tend to be flood dominant, which tends to favor the introduction of additional marine sediment into these systems, increasing their tendency to remain shallow. Conversely, deep creek systems tend to be ebb dominant, which tends to decrease the import of marine sediment, increasing their tendency to remain deep. Within individual tidal marshes, the shallower channels are more likely to be flood dominant, whereas the deepest channels are more likely to be ebb dominant, a pattern which is reinforced by the tidal distortion itself. Even across a single channel consisting of a shoal and a deep, the shoal is more likely to be flood dominant, while the deep is more likely to be ebb dominant (FRIEDRICHS *et al.*, 1992).

The association between dominance type and marsh elevation argued for in the previous section is also a potential source of positive feedback. Assuming channels which are, on average, flood dominant are also associated with high marsh, then the dynamics which produce tidal asymmetry in such systems will be affected by large areas of intertidal storage only on the highest spring tides. This means that for the vast majority of the time, the marsh channels will remain strongly flood dominant, continually delivering fine sediment to the inner marsh creeks where it will wait to be finally transferred to the marsh during the occasional overtopping of the channel levees. Assuming channels which are, on average, ebb dominant are associated with low marsh, then intertidal storage in the marsh will strengthen ebb dominance on the majority of tidal cycles. (Marshes are not absolutely necessary for ebb dominance since intertidal flats can alternatively supply sufficient intertidal storage.) The very presence of the low marsh will favor export of sediment in the channel, further discouraging the accretion of higher marsh (see Figure 27).

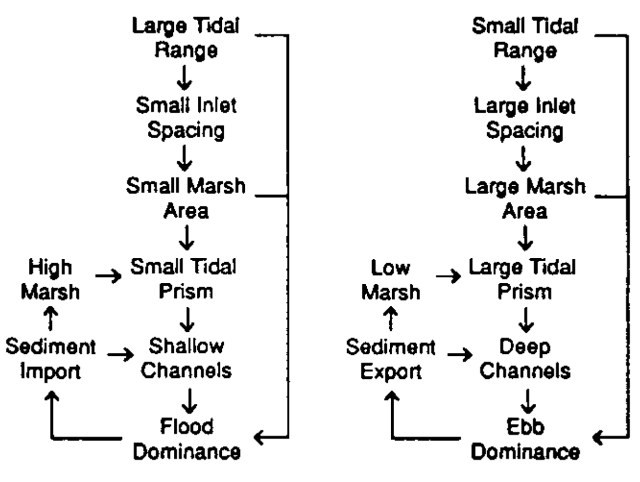

Figure 27. Morphodynamic relationships between tidal range, inlet spacing, marsh size, tidal prism, channel depth, flood- or ebb-dominance, marsh sediment supply and equilibrium marsh height.

Evolutionary Shifts Between Dominance Type

The previous paragraph addresses "equilibrium" tidal embayments. During the initial phase of lagoon infilling, it is possible that expansion of intertidal marsh may eventually lead to a shift from ebb to flood dominance (BOON and BYRNE, 1981; STEVENSON *et al.*, 1988; LESSA and MASSELINK, 1995). If one imagines a lagoon that is partially filled in with marsh, $\Delta b/\bar{b}$ might be small enough relative to $\Delta h/\bar{h}$ that the major tidal channel connecting the lagoon to the sea might be flood dominant. This arrangement would accelerate delivery of sediment to the lagoon and accelerate the expansion of the marsh. With expansion of the marsh, $\Delta b/\bar{b}$ would grow until it conceivably exceeded $\Delta h/\bar{h}$. Then ebb dominance would reduce the supply of sediment to the marsh and perhaps limit further marsh expansion. This evolutionary pattern could also work in reverse. A lagoon that was losing marsh area due to relative sea level rise might find its $\Delta b/\bar{b}$ ratio decreasing relative to $\Delta h/\bar{h}$. With time, the system might switch back to flood-dominance, which might provide the additional sediment necessary to prevent complete submersion. Increasing the depth of the seaward channels of an embayment by dredging may also cause a shift to ebb-dominance (VAN DER SPEK, 1997) because dredging will reduce $\Delta h/\bar{h}$ relative to $\Delta b/\bar{b}$.

Balance Between Temporal and Spatial Velocity Asymmetry

It is possible that in some tidal marshes, a morphodynamic balance is achieved between flood- or ebb-dominance and along-channel gradients in tidal velocity amplitude. FRIEDRICHS (1995) noted that flood-dominant tidal channels tend to exhibit an increase in peak bottom stress with distance landward. In these cases, landward sediment transport associated with flood-dominance may be partially balanced by seaward sediment transport associated with scour/settling lag. It is reasonable to speculate that in ebb-dominant marsh channels, a general decrease in tidal velocity amplitude with landward distance may allow scour/settling lag to help compensate for the tendency of ebb-dominance to export sediment. If present simultaneously, one can also expect scour/settling lag and flood or ebb dominance to act preferentially on different sediment grain sizes. Coarser sediment is more sensitive to local velocity dominance, whereas fine sediment is more sensitive to scour/settling lag (RIDDERINKHOF, 1997). ZARILLO (1985) and FRENCH and STODDART (1992) concluded that a combination of ebb dominance and scour/settling lag caused simultaneous seaward transport of sand and landward transport of mud in Georgia, U.S.A., and North Norfolk, U.K., marsh channels, respectively.

BASIN AND LARGER SCALE EFFECTS

Pre-existing Geological Control and Shelf Morphology

The tidal prism exiting an inlet from a marsh-lagoon system during extremely high tides and/or surges is determined in large part by geological constraints of the overall basin geometry (FRIEDRICHS *et al.*, 1992). Because of the constraints tidal prism places on equilibrium tidal channel morphology, smaller inlet/marsh systems that form with limited tidal prisms will tend to have shallower channels, whereas larger systems with relict morphology that dictates a larger tidal prism will have deeper channels. In basins forced by similar offshore tidal amplitudes, the arguments of the previous sections then tell us that large marshes will tend to have ebb-dominant main channels, while small marshes will tend to have flood-dominant main channels. This tendency for small tidal embayments to be flood dominant while large embayments tend to be ebb dominant is empirically evident in the survey of tidal data from U.S. Atlantic Coast inlet/marsh systems presented by FRIEDRICHS and AUBREY (1988).

As discussed earlier, flood-dominant channels are likely to deliver more marine sediment into the inner marsh, maintain higher suspended sediment concentrations immediately adjacent to the marsh, and maintain a higher marsh elevation at equilibrium than are ebb-dominant channels. Thus it follows that all else being equal, smaller inlet/marsh systems will be characterized by a larger percentage of high marsh than will larger inlet/marsh systems. The tendency for small inlet/marsh systems to be flood dominant may partially explain why typically small New England marshes tend to have a larger percentage of high marsh than do typically larger marshes along the Mid- and South-Atlantic Bights. Antecedent glacial geology in New England has resulted in small basins associated with hummocky till deposits in the south and a steep rocky coast in the north. The result is a predominance of small, flood dominant embayments (FRIEDRICHS and AUBREY, 1988). In contrast, to the south of Long Island, the coastal plain along the U.S. east coast is generally wide and gently sloping, accommodating larger marsh/inlet systems which are more commonly ebb dominant (FRIEDRICHS and AUBREY, 1988).

Since the width of the continental shelf and general shape of the coast line is associated with the regional tidal range (HAYES, 1979), certain shelf and coastline morphologies should ultimately favor high or low equilibrium marshes, respectively. Wide shelves and/or embayed coasts tend to favor a larger tidal range at the coast (e.g., the German Bight, the New York Bight), while narrow shelves and/or lobate coasts tend to favor a smaller tidal range at the coast (e.g., the coasts of Maryland and New Jersey). Thus it follows that intertidal areas along embayed coasts should tend to have higher equilibrium marsh than intertidal areas along lobate coasts.

Tidal Range and Basin Area Along Barrier Beach Coastlines

Along barrier beach coastlines, the tidal prism passing through a single tidal inlet is determined in large part by the spacing of tidal inlets. The spacing of tidal inlets, in turn, is determined largely by the tidal range (HAYES, 1979; FITZGERALD, 1988). The spacing of tidal inlets cannot become too large for a given coastal tidal range because the resulting difference in head across the island due to dampening of the lagoon tide will eventually become too great to prevent short term storm overwashes from forming permanent new inlets (FRIEDRICHS *et al.*, 1993). The equilibrium spacing between inlets is determined by a morphodynamic balance between a tendency of the tide to maintain inlets and the tendency of along shore drift driven by wind waves to close them (HAYES, 1979). Assuming wave energy to vary more weakly alongshore than tidal energy, the distance between inlets (and the overall size of the lagoon/marsh tidal watershed) will vary inversely with tidal range (FITZGERALD, 1988, Figure 28).

This inverse relationship between tidal range and intertidal area will further reinforce flood dominance in systems with large tidal ranges and ebb dominance in systems with small tidal ranges (FRIEDRICHS *et al.*, 1992, Figure 27). It will likewise reinforce a positive correlation between tidal range and equilibrium marsh height. These arguments can be expected to hold mainly when comparing systems within the meso- to macro-tidal regimes. Along barrier island coastlines, micro-tidal lagoons tend to be mainly open water with very little marsh (HAYES, 1979), assuming storm surges/floods are not sufficiently common to greatly enhance marsh extent. Lagoons which are mainly open water do not strongly favor ebb dominance because the relative area of intertidal storage is small.

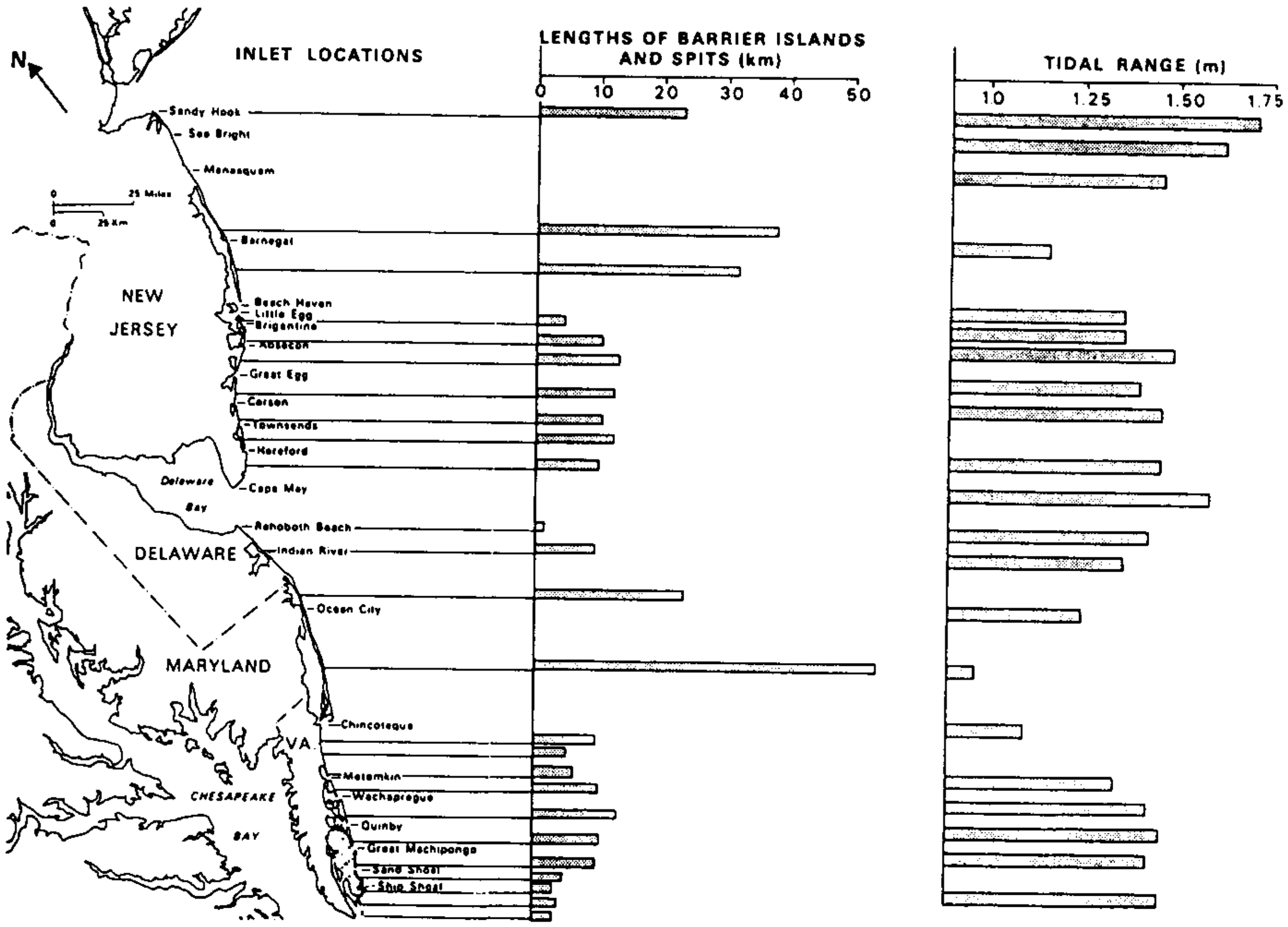

Figure 28. Plot of tidal range versus barrier island length for the New Jersey and Delmarva Peninsula coasts. Note the inverse correlation between these two parameters. From FitzGerald (1988), published with permission of *Springer-Verlag*.

SUMMARY AND CONCLUSIONS

In past decades, conceptual models of marsh evolution have shown a tendency to assign ages to tidal marshes (i.e., "youthful" versus "mature"), implying a steady and inevitable long term progression toward infilling (FREY and BASAN, 1985; FINKELSTEIN and FERLAND, 1987; ASHLEY and ZEFF, 1988). As pointed out by OERTEL *et al.*, (1992), several tenuous assumptions are inherent in such models: Rising sea level must have no significant impacts on the margins of the marsh basin; sediment supply must be steady and always sufficient to allow the marsh to slowly accrete and prograde; tidal prism cannot increase with sea level rise, but must remain steady or gradually decrease. Over the last fifteen years, the literature has better recognized the truly dynamic nature of tidal marsh morphology. The corollary of this conclusion regarding tidal marsh morphodynamics is that engineered marshes which are not initially in dynamic equilibrium with physical forcing may very rapidly evolve away from their initial designs. It is encouraging to note that within the last five years, an increasing number of authors have begun to apply concepts of morphodynamics to the design and evaluation of engineered tidal salt marshes.

Some of the most important marsh processes and properties which often lead to the maintenance of a near dynamic equilibrium include:

1. Marsh grass reduces the velocity of flow so drastically that sedimentation usually occurs continually throughout the period of inundation. With increased grass density, sedimentation increases further.
2. The supply of sediment to the marsh surface is proportional to the concentration of suspended sediment adjacent to the marsh, and the deposition rate generally decreases with distance away from that source.

3. The total amount of sediment deposited on a marsh is proportional to the total duration of inundation, and the allochthonous deposition rate generally decreases with increasing local marsh elevation.
4. Because deposition is proportional to inundation, inorganic accretion tends to increase or decrease with accelerated or decelerated sea level rise, allowing the accretion rate to fluctuate along with changes in sea level.
5. Marshes with reduced sediment supply or enhanced subsidence will therefore accelerate their accretion rate (to a finite degree) by establishing a relatively lower elevation at equilibrium.
6. Feedback between proximity to source and duration of inundation allows spatially uniform long term accretion if marsh elevation decreases away from the banks of marsh creeks.
7. Since physical stress on vegetation generally increases with inundation, plant density and accretion of organic matter is reduced as hydroperiod increases, a pattern opposite to allochthonous sedimentation.
8. Marsh degradation is as dynamic as marsh expansion. Extreme inundation destroys the inner marsh via waterlogging, while direct attack by waves can rapidly erode the marsh edge.
9. Macrotidal marshes may best withstand sea level rise because a they tend to have higher creek velocities and be flood-dominant, both of which increase the sediment source concentration for the marsh.
10. Microtidal marshes are most reliant on storms and floods to maintain accretion. They horizontally expand and retreat most quickly because their potential vertical range is so small.
11. The density, width and depth of salt marsh creeks all increase with increased tidal prism. Marsh channels are narrower and more stable than other channels because of confining vegetation.
12. Flood-dominant creeks are associated with larger tidal range, smaller marsh extent, shallower channels and higher marsh elevation at equilibrium. The opposite holds for ebb-dominant creeks.
13. These associations are morphodynamically linked in that tidal range influences inlet spacing. Inlet spacing influences marsh size and tidal prism which, in turn, controls channel depth and tidal asymmetry.

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